A HYDROGEOLOGICAL ASSESSMENT OF THE DELAMERE SANDSHEET AND ENVIRONS

June 2003

1805/R1

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EXECUTIVE SUMMARY

The Delamere sandsheet is an extensive (c. 50 km^2) deposit of fluvioglacial sands and gravels located around 5 km south-west of Northwich, at the north-west margin of the Cheshire Plain. The majority of the sandsheet (95%) is underlain by the relatively low permeability Mercia Mudstone Group deposits, but a narrow (300-500 m) strip along its western edge is underlain by the higher permeability Helsby Sandstone (of the Sherwood Sandstone Group), which also crops out immediately to the west of the sandsheet. The sandsheet itself comprises mainly homogeneous sand with additional much smaller components of both clay and gravel. The clay component is found in horizontal bands which vary in thickness between a few centimetres and about one metre, and which are laterally persistent on the scale of a few hundred metres.

Prior to 1905, groundwater levels within the Delamere sandsheet and the adjacent Helsby Sandstone were similar at around 73 maOD. Since 1905, however, large-scale groundwater abstraction from the Helsby Sandstone for public supply has caused a lowering of groundwater levels in the Helsby Sandstone of around 30 m. Groundwater levels in the sandsheet have remained relatively unchanged.

A detailed hydrogeological characterisation of the Delamere sandsheet has shown that for the 1982-2002 period, the estimated average annual recharge was 339 mm, representing around 40% of incident rainfall. Small percentages of this recharge (between 2 and 4%) discharge as; 1) flow to the west into the Helsby Sandstone, 2) groundwater abstraction, and 3) open water evaporation from surface water bodies within aggregate extraction sites. The remainder, the large majority, discharges as baseflow to the streams running across the sandsheet in relatively deeply incised valleys.

Oakmere and Abbots Moss are both candidate Special Areas of Conservation (cSACs) located within the main body of the Delamere sandsheet. They are both internationally important lowland open water and peatland conservation sites. Under the Conservation (Natural Habitats and c.) Regulations 1994, the Environment Agency, as the competent and relevant authority, must undertake an appropriate assessment to establish whether Agency-authorised groundwater abstractions will have, or have, a significant effect either individually or in combination with other authorised activities on the Oakmere and Abbots Moss cSACs.

Detailed analysis of groundwater levels in the vicinity of Oakmere and the surface water level of Oakmere has shown that Oakmere is in good hydraulic continuity with the groundwater system, meaning that the level of Oakmere is an expression of the local water table. Whilst surface water levels have not been measured accurately at Abbots Moss, other evidence suggests that it too is in good hydraulic continuity with the groundwater system.

With regard to the Agency-authorised groundwater abstractions from the Helsby Sandstone, interpretation of various sources of evidence (including groundwater levels and C19th topographic surveys) has facilitated a partial reconstruction of the hydrogeological situation before the commencement of abstraction in 1905. Comparison of this former situation with the current situation suggests that the groundwater catchment areas for both Oakmere and Abbots Moss have not been changed by the marked fall in groundwater levels in the Helsby sandstone. In turn, this suggests that groundwater levels, and also seasonal and medium-term fluctuations in groundwater levels, have not changed. It can therefore be concluded that the Agency-authorised groundwater abstractions within the Helsby Sandstone have had no significant effect on the groundwater environments at either Oakmere or Abbots Moss.

With regard to the Agency-authorised groundwater abstractions from the Delamere sandsheet, a simple assessment procedure based on the area of hydraulic influence of each of the abstractions has been used to demonstrate that they have no influence on groundwater levels in the vicinity of either Oakmere or Abbots Moss under either average or drought climatic conditions.

In addition to Agency-authorised groundwater abstractions, a number of other possible influences on the hydrogeological environment, and therefore potentially on the conservation status of Oakmere and Abbots Moss, have been identified. These include; surface water bodies within aggregate extraction sites, groundwater abstraction under Crown Excemption by Forest Enterprise, changes in land-use in the vicinity of Oakmere and Abbots Moss. The Agency is not the competent and relevant authority in relation to any of these possible influences.

1 INTRODUCTION

1.1 Background

The requirements of the EU Birds and Habitats Directives (Council Directives 79/409/EEC on the conservation of wild birds and 92/43/EEC on the conservation of natural habitats and of wild flora and fauna) are transferred into British Law through the Conservation (Natural Habitats & c.) Regulations 1994 *(commonly referred to as the Habitats Regulations).* Under these Regulations the Environment Agency (EA), as a competent and relevant authority, must undertake an appropriate assessment where it is thought that a new or existing Agency-authorised activity will have, or has, a significant effect either individually or in combination with other authorised activities on a Special Protection Area (SPA) or a Special Area of Conservation (SAC) or other European site.

A tiered assessment process, with three stages, has been adopted for the determination of whether or not a permission is adversely affecting a site:

- Stage 1 is a very coarse initial screening exercise to filter out applications or activities that by virtue of their nature or location could not conceivably have an effect on the interest features of the site.
- Stage 2 is a significance test, a second screening exercise intended to identify those permissions and activities that require further assessment. An appropriate assessment will only be required if the permissions, either individually or in combination with other authorised activities, are believed to be having a significant adverse effect on the site.
- Stage 3 is the 'appropriate assessment'. The Habitats Regulations do not specify how the assessment should be undertaken although its purpose is to ascertain, in view of the site's conservation objectives, that the proposal would not have an adverse effect on the integrity of the site. (Habitats Directive: Work Instruction (Section 4)).

Oakmere (candidate SAC or cSAC) and Abbots Moss (part of the West Midlands Mosses cSAC) are internationally important lowland open water and peatland conservation sites located on the Delamere sandsheet, an extensive area covered by fluvio-glacial deposits located towards the north-west margin of the Cheshire Plain (Figure 1.1). An aerial photograph including the two sites is included as Figure 1.2.

Oakmere and Abbots Moss have been designated as cSACs for their oligotrophic and dystrophic waters which are rare in England. This water chemistry is associated with Schwingmoor development, a characteristic of this habitat type in the West Midlands. Schwingmoor is an advancing floating raft of bog-moss *Sphagnum*, often containing NVC type M3 *Eriophorum angustifolium* bog pool community, which grows from the edge of the pool and can completely cover over the pool. Oakmere and Abbots Moss are considered to be two of the best areas in the UK for Schwingmoor which has developed into transition mires and quaking bogs.

Stage 1 assessments for both Oakmere and Abbots Moss identified relevant permissions (e.g., Agency-authorised groundwater abstractions) based on a number of criteria. The most relevant of these criteria with respect to groundwater abstractions was; 'any licences within 3 km of the perimeter of the site boundary, from both surface and groundwater sources, in accordance with Water Resources Trans-Regional Action Group Guidance Document'.

Stage 2 assessment identified all of the groundwater abstractions within 3 km of both Oakmere and Abbots Moss as 'likely to have a significant effect' but not yet clearly assessed as having 'significant impact'.

Since the possibility of Agency-permitted groundwater abstractions having a significant impact on Oakmere and/or Abbots Moss had not been discounted in the Stage 2 assessment, a Stage 3 'appropriate assessment' was required.

1.2 Scope of work

The overall objective of the study is to carry out Stage 3 appropriate assessments, under the EU Habitats Directive (92/43/EEC), of the influence of activities permitted by the Agency relating to groundwater on cSACs located on the Delamere sandsheet, Cheshire. The specific objectives are:

- To develop a conceptual model.
- To produce recommendations for further hydrogeological assessment.
- To carry out this further assessment, in a manner to be agreed with the Agency.
- To undertake a technical review of an ongoing Agency groundwater assessment of the adjacent sandstone aquifer, specifically addressing the effects on the cSACs of historical groundwater abstraction from the main aquifer.
- To produce a technical report which will form the basis of the 'appropriate assessment' as required under Stage 3 of the Habitats Regulations.

1.3 A brief guide to the report

The solid and drift geology of the Delamere area, based on both published information and information collected during the current study, is described in Section 2. Groundwater flow and water quality are described in Section 3, including sections on groundwater levels, aquifer properties, groundwater discharge and hydrogeochemistry. A water balance for the sandsheet for the period 2001-2002 is presented in Section 4, and the hydrogeological conceptual model of the area is described in Section 5. The assessment of the possible impacts of Agency-permitted groundwater abstractions on Oakmere and Abbots Moss is presented in Section 6 whilst conclusions and recommendations are given in Section 7.

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Figure 1.1 Location of Oakmere and Abbots Moss cSACs

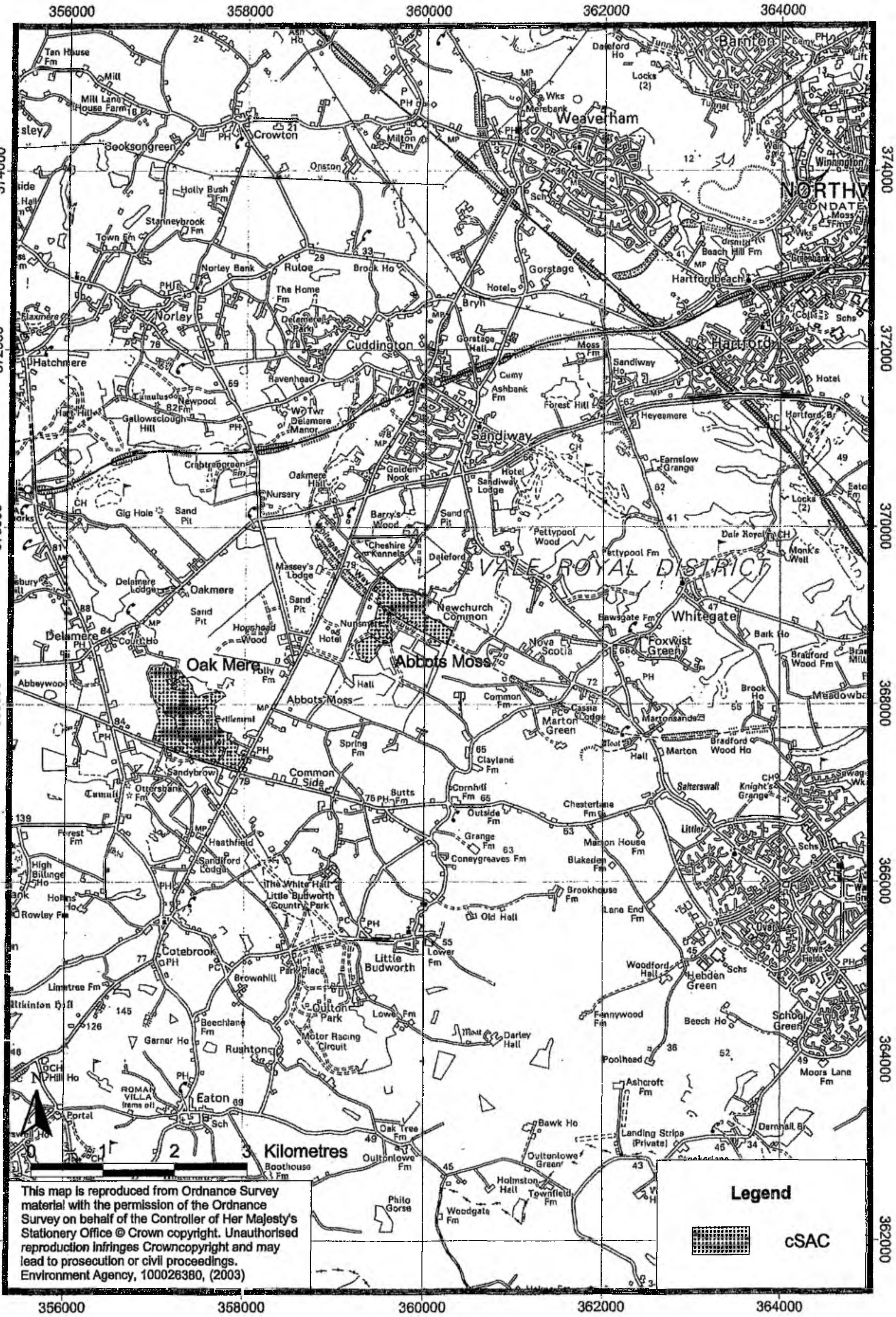

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Figure 1.2 Aerial photograph of area including Oakmere and Abbots Moss cSACs

2 GEOLOGY, TOPOGRAPHY AND LAND-USE

2.1 Geology

2.1.1 Solid geology

Review of published information

Figure 2.1 is an extract from the 1:50,000 map of the solid geology (BGS, Sheet 109). Figures 2.2 and 2.3 are three-dimensional visualisations of the land surface (developed from the Ordnance Survey 'Profile' DEM) with the outcropping solid/drift geology 'draped' over the land surface.

The solid geology of the area (Figure 2.1) consists of two main units brought into contact by the East Delamere fault. To the west of the East Delamere fault the upthrown higher permeability Helsby Sandstone (Sherwood Sandstone Group) crops out, forming the topographic high of the mid-Cheshire ridge (Figures 2.2 and 2.3). To the east of the fault the less permeable Northwich Halite (Mercia Mudstone Group), including siltstones, mudstones and occasional thick beds of rock salt, is mainly covered with drift.

It should be noted that the positions of some of the faults on the published geological maps of the area had been proved to be inaccurate, and in 1999 the British Geological Survey re-assessed and re-mapped the geological structures in the area (Chadwick *et al*, 1999). This led to the East Delamere fault being remapped as a fault zone extending 200 m east of its originally-mapped position. The relocation brings the fault directly under the western edge of Oakmere SSSI. Several other faults, which were not apparent on the original survey, have also been mapped. The East Delamere Fault is shown in its revised position and configuration in Figure 2.1.

2.1.2 Drift geology

Review of published information

Published information on the drift deposits of the area is available from two main sources, the geological memoir (Earp and Taylor, 1986) and the latest hydrogeological conceptual model of the Wirral and West Cheshire areas (LWRC, 2000). The following description is based on these two sources.

The drift sequence in the area comprises three main components; Lower Boulder Clay, Middle Sands and Upper Boulder Clay (Hull, 1864). It is generally accepted that this sequence is the result of one glacial advance and retreat with, in broad terms, the Lower Boulder Clay deposited during the advance, the Middle Sands deposited during the retreat and the Upper Boulder Clay being melt-out till and flow till redistributed during the later retreat phase. The drift deposits in the Delamere area are accepted to have been entirely deposited by Irish Sea ice moving over the area from the north-west.

It is recognised that the bedrock in the Dee/Mersey area has significant relief (e.g.. Grayson 1972), with the bases of glacially eroded channels being well over 50 m below present sea levels and current ground surfaces at outcrop rising to over 100 m. Although the larger-scale regional form of the rockhead topography is known (e.g.. LWRC, Figure 1.5.3), the relative paucity of deeper boreholes means that its exact local form remains uncertain. The effect of the extensive blanket of drift deposits is to considerably smooth out the relief of the rockhead.

The most important component of the drift deposits in the area in relation to the current study is the Middle Sands, a large proportion of which form the Delamere sandsheet (Figure 2.4). The sandsheet is believed to have been formed when drainage waters from the Quaternary glaciers were impounded by ice fronts and rock ridges. This impoundment lasted long enough to deposit the outwash sands and gravels which now form the sandsheet. Ridges in the sand remain, representing dominant channels in the braided stream system. The sands also exhibit slumping and faulting on a small scale. These structures are believed to have been caused by the sand collapsing as the ice supporting it started to melt. Another possibility for the origin of the more defined faults is that the faulting occurred when the sand was a solid mass with an ice matrix.

Borehole records (e.g., Earp and Taylor, 1986) show the drift to be over 90 m thick in the centre of the sandsheet.

Layers of clay are present in the sandsheet, mainly within the top 30 m. For example, a laterally extensive clay layer with a thickness of around one metre has been traced at an elevation of 50 maOD. The clay layers within the outwash deposits are thought to be flow till which remained in place during the glacial retreat phase (because of a temporary variation in the drainage pattern) to be covered by further outwash material (Earp and Taylor, 1986).

The majority of the sandsheet is located over the subcrop of the Mercia Mudstone Group formations (Figure 2.4), with a small strip to the west of the East Delamere Fault overlying the subcrop of the Helsby Sandstone.

Borehole evidence suggests that the Lower Boulder Clay beneath the Delamere sandsheet is patchy. Of most importance in relation to the current study is the 5 m of stony till proved in three deep boreholes beneath the sandsheet in the vicinity of Oakmere. Earp and Taylor (1986, Figure 24, Sections 1-3) suggest that a strip of Lower Boulder Clay 1 to 1.5 km wide extends roughly parallel to the surface contact between the sandsheet and the Sherwood Sandstone, being present beneath Oakmere.

Figure 2.4 shows that at outcrop the sandsheet is surrounded by Boulder Clay. Earp and Taylor (1986, Figure 24) suggest that over the majority of the area this is the Upper Boulder Clay. They also suggest that the Middle Sands are not laterally continuous and that they tend to pinch out within the Upper Boulder Clay.

The remaining drift is peat lying in local topographic depressions, such as Oakmere and Abbots Moss. At Oakmere the peat deposits cover a much larger area than the current lake, and a map of Oakmere from 1817 confirms that the lake used to cover the entire area of peat.

New information

Whilst a good deal of general information is available from the literature on the sandsheet, there is very little detailed information on the morphology and lithology of the deposit. In order to develop a 'best-possible' characterisation of the sandsheet, geological logs were collected for all relevant boreholes. Available sources included appendices in the geological memoir (Earp and Taylor, 1986), the EA (recently installed piezometers) and Cheshire County Council (mineral exploration borehole logs included in planning applications). The geological logs were reviewed and interpreted before relevant details were entered into a database.

The locations of boreholes for which geological logs were available are shown in Figure 2.5 and details of the sources of the geological logs are given in Table 2.1. Figure 2.5 shows that the distribution of boreholes for which geological logs were available is not ideal as there is no coverage over large areas of the sandsheet.

The main aims of the geological investigation were to:

1) Characterise the three-dimensional basal surface of the sandsheet (i.e., its contact with either the Mercia Mudstones or the Lower Boulder Clay) and, through comparison with the ground surface, develop an understanding of the spatial variation of the thickness of the sandsheet.

2) Characterise the three-dimensional variation in lithology within the sandsheet, with specific reference to corresponding variation in hydraulic properties.

Figures 2.6 and 2.7 are three-dimensional images developed using ArcView (GIS software) of the geological logs, along with the topographic surface.

With regard to the first aim, logs were available for only four boreholes which extended to the base of the sandsheet. The majority of the boreholes are 30 m or less deep. In the case of the mineral exploration boreholes their depth is related to the maximum permitted depth of sand extraction, whilst the Agency boreholes were designed to investigate relatively shallow hydrogeological dynamics within the sandsheet.

The interpreted elevation of the base of the sandsheet in the four deep boreholes is -12.3, 44.4, 26.8 and 43.1 maOD. Given; a) the small number of borehole logs, b) the significant variation in the elevation of the base of the sandsheet in these logs, and c) the knowledge that the rockhead beneath the sandsheet is likely to have significant relief, it was decided unwise to interpolate between the datapoints to develop a three-dimensional surface representing the base of the sandsheet. The thickness of the sandsheet as proved in the four deep boreholes is between 29 and 75.6 m with a mean value of 43.9 m.

Table 2.1 Details of boreholes and borehole groups for which geological logs were available

Name	Source of log	National Grid Reference	No. of boreholes	Depth/Max depth
Austin's Springs	Memoir*	5952 6722	1	455.5
Bowyer's Waste	Memoir	5686 6882	1	193.1
Crabtree Green	Memoir	5797 7084	1	351.1
Oakmere	Memoir	5768 6780	1	213.7
Fourways Quarry	CCC	various	22	29.95
Crown Farm Quarry	CCC	various	22	30
Cherry Orchard Sand Unit	CCC	various	7	28
Oakmere OBHs	EA	various	7	20.5
Abbots Moss OBHs	EA	various	7	15
Fishpool Quarry	CCC	various	18	22.8
Cobden Farm Quarry	CCC	various	7	30
Sandiway Quarry	EA	various	10	23

** Earp and Taylor, 1986*

With regard to the second aim, a number of issues were identified:

1) The geological logs for any one group of boreholes had a consistent description of the dominant sand-rich horizons. This description varied between groups of boreholes (see colour clustering in Figures 2.6 and 2.7), but it was decided that this probably reflected variation in the way different personnel had described the lithology rather than a real difference in lithology. It was therefore decided that the qualitative lithological descriptors were not sensitive enough to identify three-dimensional variations in lithology with any certainty.

2) The geological logs for some groups of boreholes are more detailed than for others with, for example, descriptions of numerous thin clay layers. It is unlikely that such clay layers are present exclusively in certain areas, and it was therefore concluded that there was a significant variation in the detail with which boreholes had been logged.

These problems meant that the three-dimensional variation in lithology could not be characterised extensively in any detail. However, it was possible to derive some conclusions relating to the lithology and associated hydraulic properties of the sandsheet:

- The overwhelming majority of borehole logs describe the sand fraction as being of fine to medium grade, and in most of the boreholes an unusual 'fining downwards' tendency is apparent with boreholes often finishing in silty sand. Even in boreholes apparently logged with finer detail, significant thicknesses (frequently over 5 m) of uniform sand are recorded.

- For the groups of boreholes which were apparently logged in relatively fine detail, there are a significant numbers of clay layers recorded. However, in only a few cases did these clay layers appear to extend across a significant number of the boreholes. It is concluded from this that the majority of clay layers within the sandsheet extend laterally on the scale of a few hundred metres. This relatively small scale of variation is consistent with the somewhat chaotic supposed depositional environment of glacial outwash channels intercalated with residual tills.

In Figures 2.2 and 2.3, a long linear step feature, with a height of around 1 m, can be seen running through the surface topography, passing just to the west of Oakmere. It is interesting to note that this feature lies directly over the newly-mapped position of the East Delamere Fault beneath the sandsheet, even where the fault curves towards the north-west to the north of Oakmere. It is also interesting to note that the 'up-throw' of the step to the west is the same as that of the underlying fault. It is tempting to hypothesise that the step in the surface topography is a result of post-glacial movement of the East Delamere Fault. Confirmation of the plausibility of this hypothesis was sought but was not available at the time of writing.

2.2 Topography

Figure 2.8 is an extract from the 1:10,000 Ordnance Survey map of the area (Explorer Series, Sheet 267). Along with Figures 2.6 and 2.7, it shows that the top surface of the sandsheet is relatively flat, lying at an elevation of between 75 and 80 maOD. Ground levels fall sharply at the edge of the sandsheet to around 60 maOD on the top surface of the surrounding Upper Boulder Clay. The sandsheet is incised with steep-sided valleys which have cut down up to 10 m into the original surface.

Immediately to the west of the sandsheet, the mid-Cheshire Ridge rises to a height of over 175 m.

2.3 Land-use

Land-use information was taken from the Land Cover Map (for 2000)(LCM 2000, Centre for Ecology and Hydrology) and the Edinburgh University Parish crop returns.

The LCM 2000 land cover map shows the following percentage land uses over the Delamere sandsheet:

- Grassland: 45%.
- Woodland: 20%.
- Arable:16%.
- Open water: 4%.
- Urban/suburban: 10%.
- Other: 5%.

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Figure 2.1 Solid geology of the Delamere district

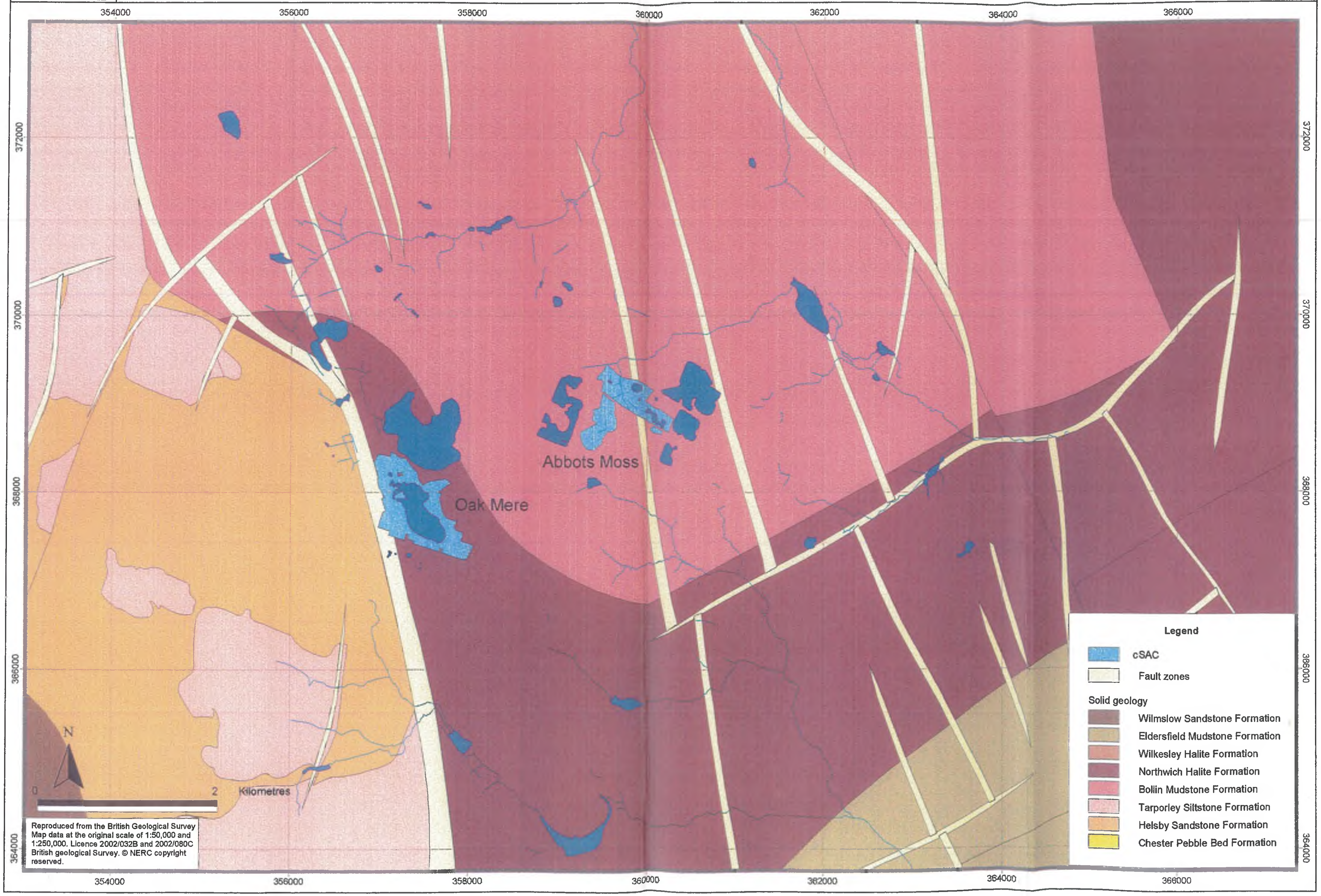

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Figure 2.2.dwg

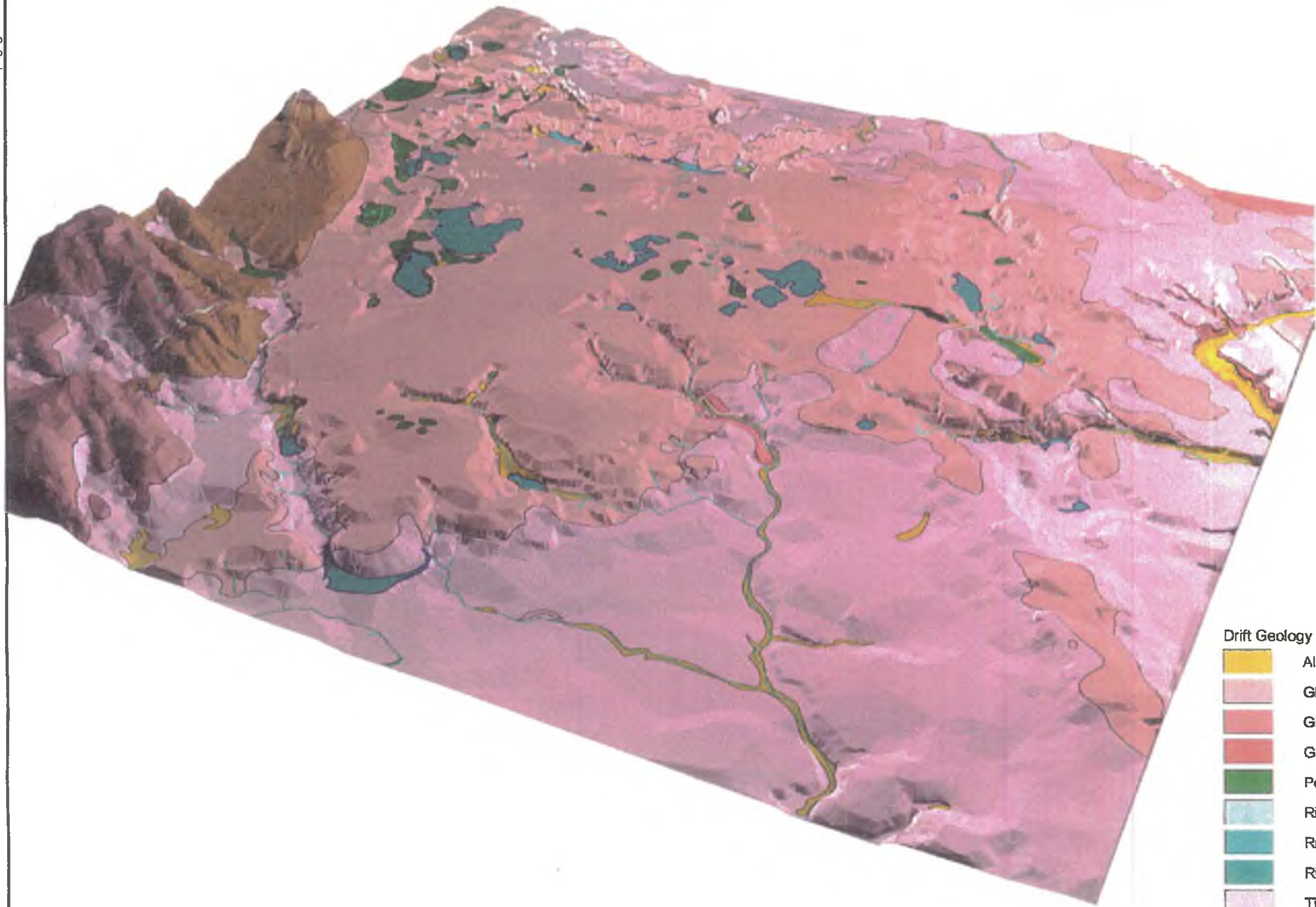

Figure 2.2 3D visualisation with 'draped' geology (from south)

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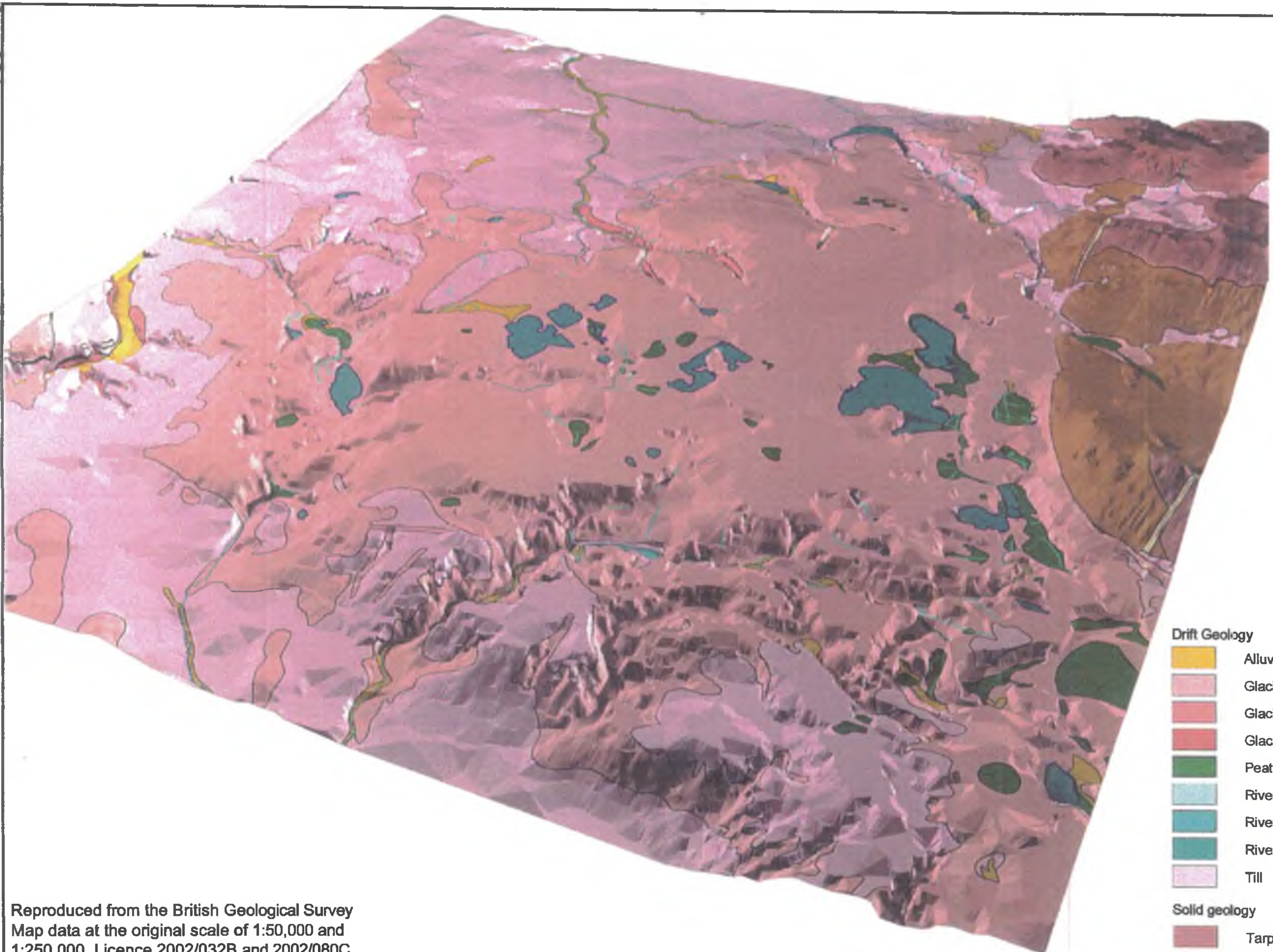

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Figure 2.3 3D visualisation with 'draped' geology (from north)

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Figure 2.4 Drift geology of the Delamere district

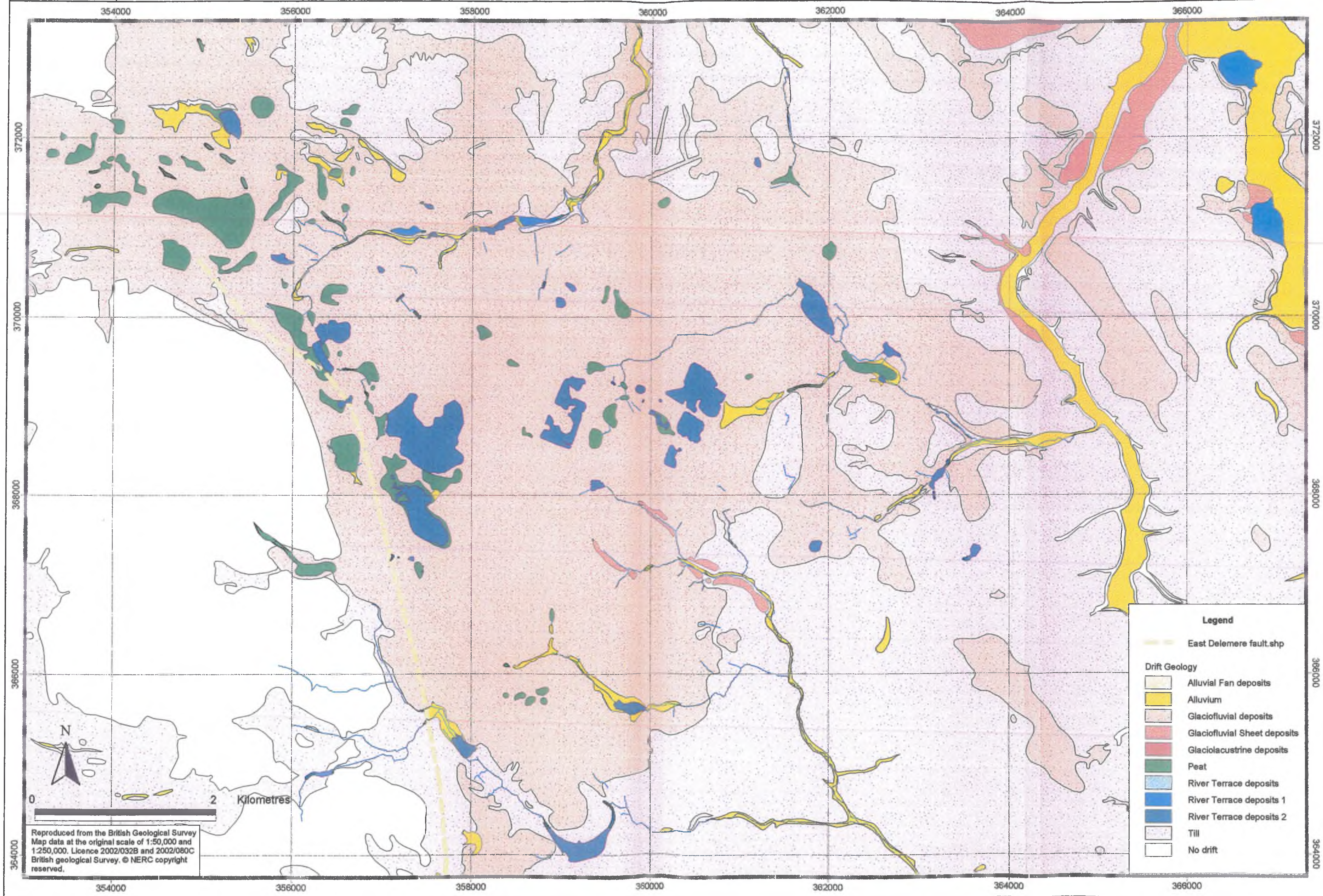

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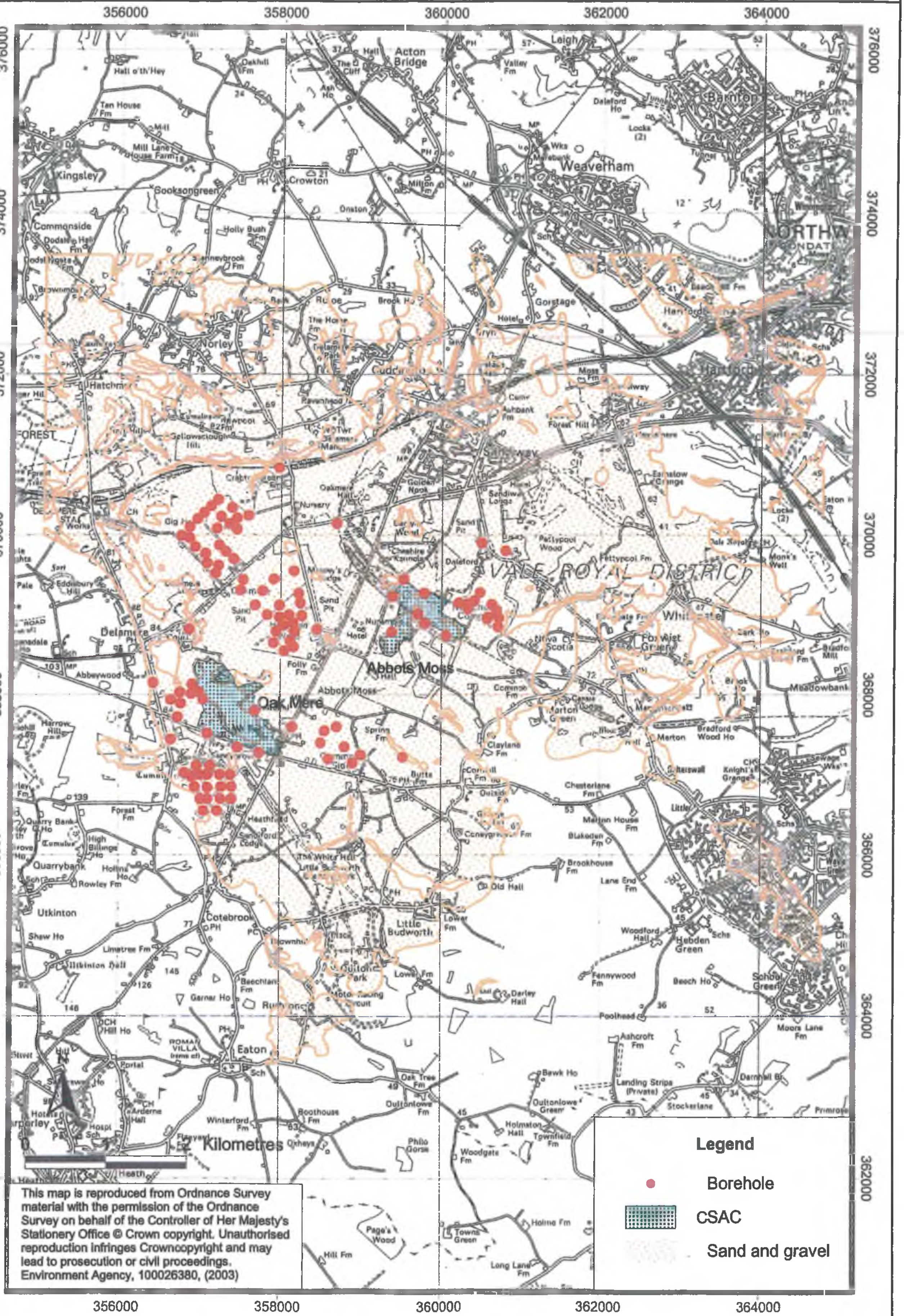
Figure 2.5 Location of boreholes for which geological logs were available



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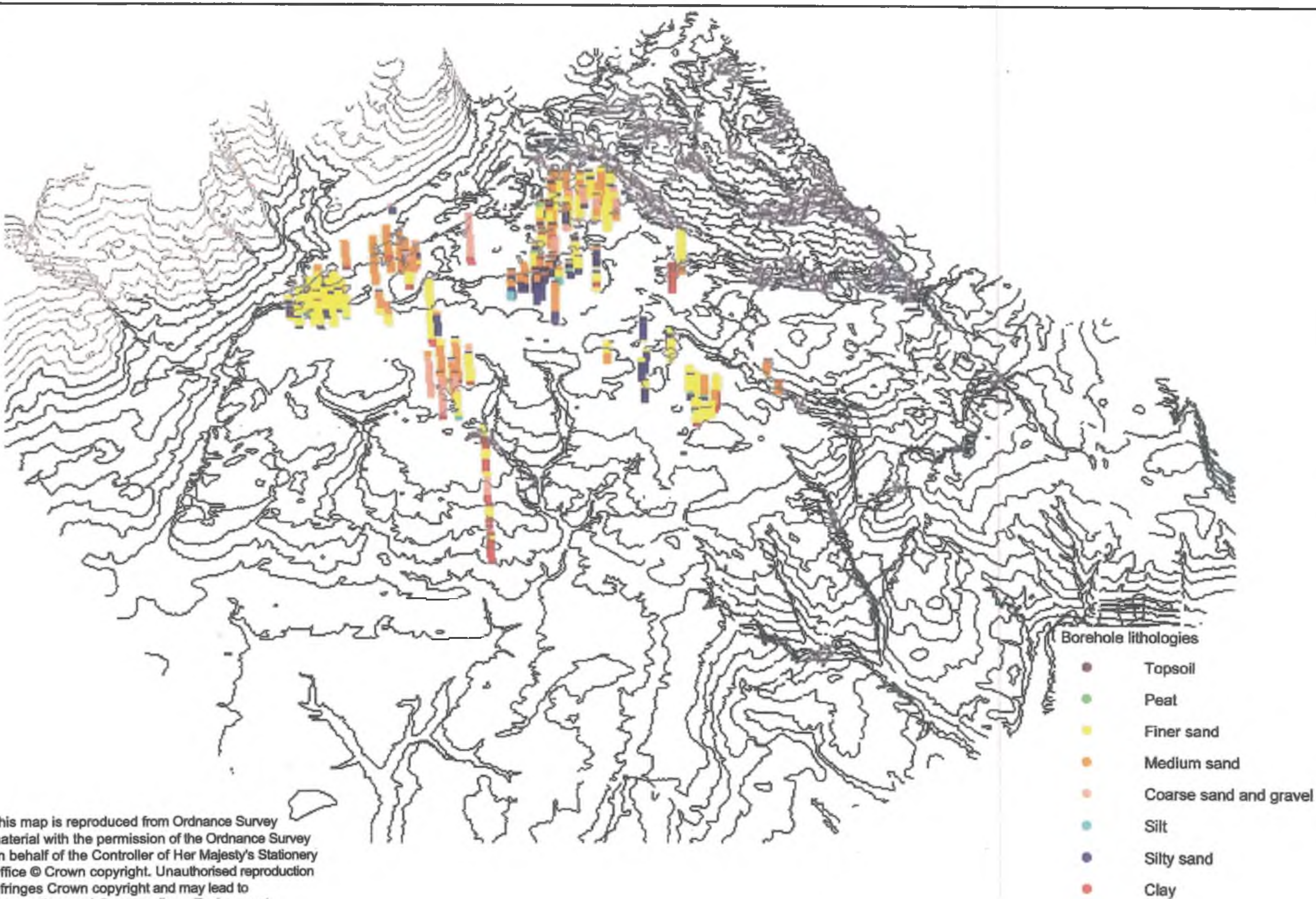

Figure 2.6 3D view of borehole logs from the south

Figure 2.6.dwg

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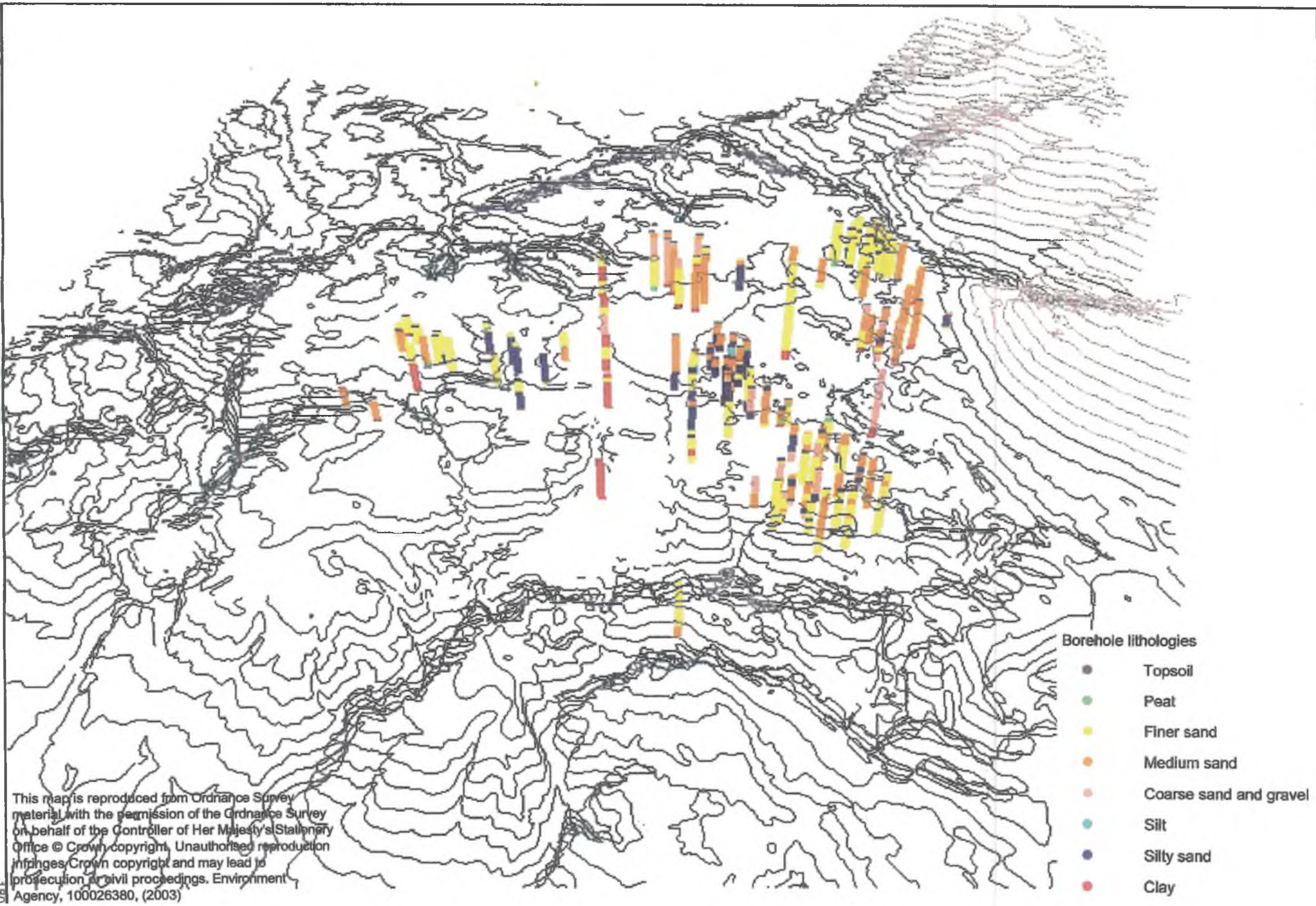

Figure 2.7 3D view of borehole logs from the north

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Figure 2.7.dwg

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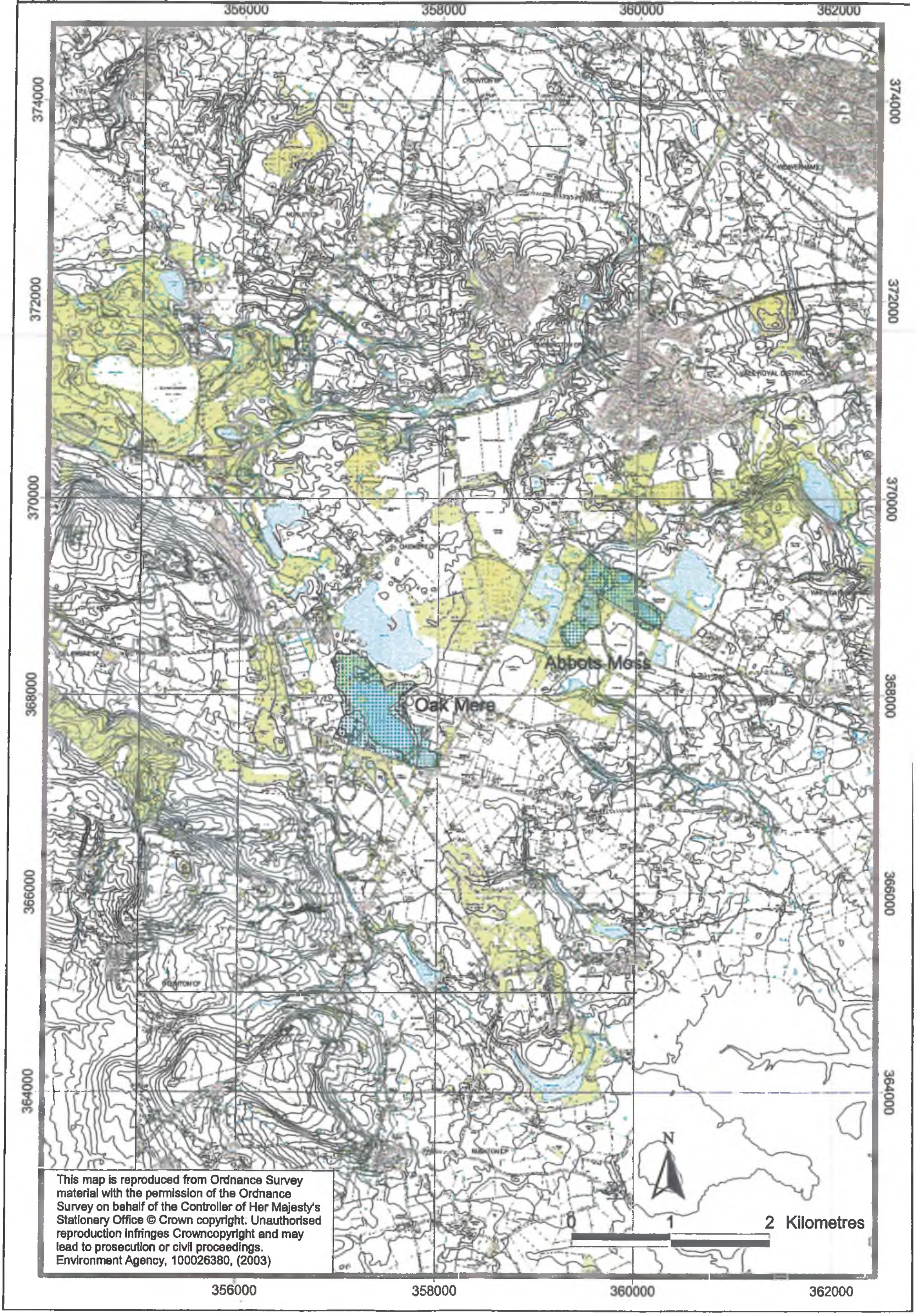
Figure 2.8 Extract from the 1:10,000 OS Survey map - Delamere area



3 GROUNDWATER FLOW AND WATER QUALITY

3.1 Groundwater flow

3.1.1 Regional groundwater dynamics

Figure 3.1 shows the locations of boreholes for which groundwater levels have been obtained. These boreholes fall into two categories:

1) A subset of the mineral exploration boreholes for which geological logs were available. The requirement for groundwater level monitoring during the operational life of a quarry is included in planning consents. Groundwater levels are usually monitored on a frequency of between two weeks and one month in these boreholes.

2) The Agency piezometers around Oakmere and Abbots Moss. These piezometers are fitted with pressure transducers and data loggers, and are set to record levels every four hours. This data was assessed in raw form to identify any shorter term groundwater level fluctuations but was 'distilled' to one reading every two days for general hydrograph analysis.

Figure 3.1 shows that the groundwater and surface water monitoring points are located exclusively in the central, west-central and north-western areas of the sandsheet. There are no monitoring points over large areas of the sandsheet, e.g., most of its eastern half.

Figure 3.2 is a composite hydrograph which includes at least one water level record from each of the groups of monitoring points (i.e., boreholes and lakes). It can be seen from this figure that each group of monitoring points within the sandsheet has a slightly different period of record and, importantly, that relatively few of these periods coincide. In order to develop a 'best-possible' groundwater level contour map, the following approach was adopted:

1) Identify the historical date (April 2002) on which the maximum number of monitoring points were active.

2) Interpolate levels from the other points to estimate a level for this date.

The general similarity of response for groups of monitoring points where their periods of record coincide (Figure 3.2) demonstrates that interpolation of levels is a valid approach in this case. Figure 3.3 is the resulting groundwater level contour map for April 2002. It shows that the highest groundwater levels in the area (>73 maOD) occur over a small area which includes the southern portion of Oakmere and areas immediately to the east, west and south of this. This area represents a groundwater level high within the sandsheet, with groundwater levels falling in all directions away from it. From the limited spatial coverage of groundwater levels it would appear that the hydraulic gradient within the sandsheet steepens quite sharply in the vicinity of groundwater discharge points. Relatively low gradients exist in the centre of the monitored area (north-east of Oakmere) whilst steeper gradients exist, both to the north and south-west close to groundwater discharge points within the incised valleys in the sandsheet, and to the south-west where groundwater from the sandsheet discharges into the underlying Sherwood Sandstone.

Groundwater levels in the Sherwood Sandstone immediately to the west of the East Delamere Fault were recorded as c. 73 maOD in 1905, i.e., very similar to levels in the Delamere sandsheet. However, levels in the sandstone have now fallen to around 46 maOD, i.e. just under 30 m below the current groundwater level in the sandsheet, under the influence of prolonged groundwater abstraction for public supply.

3.1.2 Groundwater and surface water dynamics local to Oakmere and Abbots Moss

Figure 3.4 presents groundwater level hydrographs for the seven Agency piezometers adjacent to Oakmere (locations shown on Figure 3.1). The hydrographs have been presented using the raw (four-hourly) data. The following observations can be made on this figure:

- All of the piezometers have a common short-term 'noise' signature caused by pulses of recharge transmitted through the thin (< 5m) high permeability unsaturated zone.
- The hydrographs for piezometers F and G have a very different character to the rest of the piezometers. They have a relatively subdued response during the period of record, and their respective peaks in groundwater level during 2002 occur up to six weeks after the equivalent peak in the other piezometers. The most probable explanation for this difference in character is that these two piezometers are located much closer to the area of groundwater discharge from the sandsheet into the underlying Sherwood Sandstone. Indeed, whilst being completed within the sandsheet, these piezometers are located over the subcrop of the Sherwood Sandstone to the west of the East Delamere Fault.
- The hydrographs for piezometers A, B, C, D and E, whilst having a very different character to those for piezometers F and G as a group, exhibit some significant differences in character. These differences include variation in the amplitude of response and varied timing of peak and trough in groundwater level during 2002. Detailed examination of the hydrographs suggest that these differences in character could be a function of the piezometers' distance from the discharge zone to the Sherwood Sandstone. For example, piezometer E, located furthest from the discharge zone, has the highest amplitude response, whilst the amplitude of response of piezometer B, located close to the discharge zone, is relatively low. The fact that there are exceptions to this trend mean that this interpretation remains uncertain.

- The behaviour of groundwater levels in piezometer D became erratic during September 2002 with diurnal fluctuations of 5-8 cm. It is not known whether this was caused by an instrument fault or whether it represents real groundwater level fluctuations on this timescale.

Figure 3.5 presents the seven groundwater level hydrographs for the Agency piezometers adjacent to Abbots Moss. Again, the hydrographs have been presented using the raw (four-hourly) data. The following observations can be made on this figure:

- The hydrograph responses of the piezometers adjacent to Abbots Moss are much more varied and erratic than those for the piezometers around Oakmere.
- Groundwater levels in piezometers B and C have fallen suddenly on a number of occasions when their data-loggers have been downloaded. It is thought that the hydraulic connection of these piezometers with their surrounding formations has been somewhat compromised, causing the water level in the piezometer to become perched as local groundwater levels fell (see Section 3.1.2). Unfortunately, it is not known how this error has built up between data-logger downloads, and therefore the recorded data is of limited use with regard to interpretation of longer-term groundwater level fluctuation.
- Groundwater levels in piezometers B and C exhibit marked diurnal fluctuations of around 5 cm between March and October 2002. It is not known whether these fluctuations are real or whether they are produced by instrument error. One possible cause of such fluctuations could be small daily recharge pulses caused by irrigation of trees by Forest Enterprise. It is noted that piezometers B and C are located very close to the tree nursery immediately to the east of Abbots Moss.
- Longer-term groundwater level fluctuation in most of the piezometers was as expected, with increasing groundwater levels during the spring and falling groundwater levels during the summer and autumn. However, there are also short- to medium-term fluctuations superimposed on the responses. The scale of these fluctuations (i.e., relatively sudden rises in groundwater level) varies consistently between the piezometers with the largest responses in piezometer D, followed by piezometers G, A, F and E. Examples of this behaviour are best identified in the response of piezometer D (marked on Figure 3.5). The most significant of these events occurred during early August 2002 when groundwater levels in piezometer D rose by 0.83 m in 10 days. The magnitude of this response, and also the variation in response between the piezometers, mean that it could not have been caused by recharge (assuming a specific yield of 25%, 210 mm of recharge would have been required). It is more likely to have been caused by a sudden rise in a surface water lake which has then propagated through the groundwater system. The spatial distribution of the amplitude of response indicates that the perturbation in water levels originates to the north of the piezometer set, and that it is not the surface waters in Abbots Moss. No obvious potentially responsible features can be identified on the topographic map.

One of the key aspects of the assessment of the effect of groundwater abstractions on Oakmere and Abbots Moss is an understanding of the hydraulic relationship between these sites and groundwater. In order to explore this relationship further, the water level response through time of Oakmere has been compared in detail with the equivalent groundwater level response in nearby piezometers. This comparison has been done on two timescales; 1) 1990-2001 by comparison of lake levels with groundwater levels over the wider sandsheet (Figure 3.6), 2) Dec 2001-Dec 2002 by comparison of lake levels with groundwater levels in Agency piezometers close to Oakmere (Figure 3.7).

Figure 3.6 allows comparison of the longer-term lake level record for Oakmere with appropriate typical borehole groundwater level responses from the various borehole groups (i.e., mineral extraction quarries) across the wider sandsheet. Although it is difficult to draw any detailed conclusions from this figure it can be seen that the level of Oakmere varies in general sympathy with groundwater levels over the wider sandsheet. It is also apparent that the amplitude of variation of lake levels is similar to that for groundwater levels.

Figure 3.7 allows comparison of the detailed shorter-term lake level response for Oakmere with the groundwater level responses for Oakmere piezometers B and C. The records from these piezometers were chosen as the piezometers are the closest to Oakmere. The record for piezometer D is not shown because of its atypical behaviour after August 2002. Figure 3.8 shows rainfall and estimated recharge (see Section 4.2) for the period November 2001 to August 2002.

Considering Figure 3.7, it should first be re-emphasised that the hydrograph responses of the Agency piezometers surrounding Oakmere during 2002 were quite varied, and therefore it has not been possible to compare the behaviour of the lake level with a typical groundwater level response. Indeed, whilst the responses of piezometers B and C (Figure 3.7) are fairly similar, they still have some notable differences, e.g. groundwater levels in piezometer B start to fall (3 April 2002) 16 days after those in piezometer C (18 March 2002).

Despite the differences in the groundwater level responses in Figure 3.7, it is still possible to identify a very distinct lake level response compared to the groundwater level responses. The distinction between the responses mainly lies in the timing of the onset of water level rise or recession. For example, lake levels began to rise on 23 January 2002, but groundwater levels in nearby piezometers only started to rise on 16 February, demonstrating a 24 day lag. Similarly, lake levels started to fall on 1 March 2002, but groundwater levels started to fall on 18 March and 3 April 2002 in piezometers C and B respectively, demonstrating a lag of between 18 and 34 days. It is also interesting to note that the rate of water level recession appears to be faster for the groundwater than for the lake levels.

During early August 2002, groundwater levels rose by up to 11 cm in piezometers A, B, C and D (also Figure 3.4). Closer examination of the responses during this period shows that both the absolute rise in groundwater level and the timing of the onset of this rise is a function of the distance between the piezometer and Oakmere (see Table 3.1). Data for Oakmere during this period show that lake levels started to rise steeply on the afternoon of 30 July 2002, three days before groundwater levels started to rise in piezometer C, and that the total rise in levels was 14.3 cm, slightly more than the rise in groundwater levels at piezometer C. It is also evident that the two-stage rising limb of the lake levels is evident in the groundwater level response in piezometer C, but not in the other piezometers. It is concluded that a rise in the level of Oakmere (caused by four large rainfall events in early August, see Figure 3.8) caused a local recharge mound in the groundwater system. The magnitude and timing of the rise in groundwater levels are consistent with a propagation of this recharge pulse through the groundwater system. Importantly, this event demonstrates conclusively that Oakmere is in good hydraulic continuity with the groundwater system, with changes in its level causing a groundwater level response within three days in a piezometer 130 m away.

Table 3.1 Groundwater dynamics in early August 2002 around Oakmere

Piezometer	Distance from Oakmere	Rise in groundwater level (cm)	Date of onset of rise
Oakmere[1]	0	14.3	30 July
A	560	2.5	13 Aug
B	250	5.9	8 Aug
C	130	11.4	2 Aug
D	135	6.7	8 Aug
E[2]	370	0	n/a

[1] *lake level*
[2] *located closer to Oakmere than piezometer A but upgradient.*

The conclusion that Oakmere is in good hydraulic continuity with the groundwater system can be confirmed by consideration on a more fundamental level of its water balance. Given that long-term rainfall (840 mm/a) significantly exceeds long-term open-water evaporation (560 mm/a), and that there are no surface water discharges from Oakmere, it is clear that a net flow of water from the lake to groundwater must occur, because otherwise the level of Oakmere would be increasing continuously.

The hydraulic continuity between Oakmere and groundwater was also demonstrated during July 1951 when 136 Ml of water were pumped into Oakmere over eight days. Lake levels approached those observed prior to the addition of the water over the next three months at a rate far in excess of that which could be explained by evaporation alone (reported in Savage *et al*, 1993).

Surface water levels in Round Pool (NGR SJ 59873 69138) and The Gullery (NGR SJ 60008 68921), which are water bodies situated to the north of the disused railway line within the Abbots Moss cSAC, are being recorded but at the time of writing the precise elevation of the recorders had not been established. Water levels in Shemmy and South Mosses, to the south of the disused railway line within Abbots Moss cSAC, are not being recorded at present.

3.1.3 Aquifer properties

Information on the hydraulic properties of the sandsheet is limited to that gained from drilling and testing of the Agency piezometers around Oakmere and Abbots Moss. Samples of aquifer material, obtained during drilling of the piezometers, were tested in a laboratory through small-scale falling head tests. Whilst these tests gave useful values it was recognised that larger-scale field hydraulic testing was required in order to reduce uncertainty on *in situ* aquifer property values. It was therefore decided, as part of the current project, to perform falling head tests in the field on the Agency piezometers. The tests were performed in late-2002. A solid PTFE slug (2 l volume) was lowered into the piezometers to instantaneously raise the water level rather than using the more uncertain method of pouring a slug of water from the top of the piezometers. The results were analysed using the Hvorslev analytical solution (Hvorslev, 1951).

Tables 3.2 and 3.3 present the results of the field and laboratory hydraulic tests for the Oakmere and Abbots Moss piezometers respectively. Considering the analytical error associated with hydraulic testing, and also the differences between laboratory and field testing, the results for Oakmere are notably consistent, with only piezometer 'A' having very different field and laboratory test results. This is interesting as field-scale tests are normally expected to yield higher values of hydraulic conductivity because of the larger-scale heterogeneities encountered in a field situation in comparison with laboratory conditions. The similarity in results would seem to indicate that the sands beneath Oakmere are relatively homogeneous, at least at a local scale around the piezometers.

Considering the field test results for Oakmere alone, it is thought that the experimental uncertainty is at least as large as the apparent variation in hydraulic conductivity, and therefore that there is unlikely to be any significant real spatial variation in the hydraulic properties.

Table 3.2 Hydraulic conductivity for the Oakmere boreholes (m/d)

	OM A	OM B	OM C	OM D	OM E	OM F	OM G
Slug test	0.1	3.5	2.4	2.1	5.0	2.2	4.5
EA dry	4.49	9.5	9.5	4.49	5.36	5.36	8.55
EA wet	0.8	0.18	1.21	0.48	4.84	0.95	0.95
EA avg	2.65	4.84	5.36	2.49	5.1	3.15	4.75

Table 3.3 Hydraulic conductivity for the Abbots Moss boreholes (m/d)

	AM A	AM B	AM C	AM E	AM F
Slug test	2.6	3.3	1.0	0.4	0.5
EA dry	11.23	1.21	19.87	3.11	6.39
EA wet	4.32	0.00	0.50	0.22	0.34
EA avg	7.78	0.61	10.19	1.67	3.37

The results for the piezometers surrounding Abbots Moss were inconsistent compared to those for the Oakmere piezometers. Of most note is the fact that for four of the five piezometers, the field-test derived hydraulic conductivity was significantly lower than the laboratory derived value. This is the opposite situation to what might be expected from scale and heterogeneity considerations. The most probable explanation for this is that the piezometers around Abbots Moss had not been developed sufficiently prior to the tests, and therefore that their hydraulic connection to the surrounding formation was somewhat compromised. On a number of occasions the act of removing the pressure transducer and the consequent perturbation in water levels had caused the water level in some of the piezometers to fall significantly as if it had been previously 'perched'. It is probable that the lower average hydraulic conductivities derived from the Abbots Moss field tests, compared to those for Oakmere[1], are a function of these piezometer effects rather than being a reflection of a significant difference in the hydraulic conductivities of the respective local formations.

The mean hydraulic conductivities derived from the field hydraulic testing for Oakmere and Abbots Moss were 2.8 and 1.6 m/d respectively. This value is in the centre of the range suggested by Freeze and Cheery (1979) for silty sand.

3.2 Groundwater discharge

3.2.1 Groundwater abstraction

Details of the groundwater abstraction licences relating to the Delamere sandsheet are given in Table 3.4, and their locations are plotted on Figure 3.9. The licences can be divided into two groups; licences to abstract large amounts of groundwater (over 1,000 Ml/a) relating to sand extraction quarries and licences to abstract relatively small amounts of groundwater (< 50 Ml/a) which is used for general agricultural and/or irrigation purposes.

Whilst abstraction 'returns' forwarded by licence holders indicate the amount of water abstracted during any time period, it is necessary for water balance purposes to estimate the percentage consumptive use of this water, i.e., what percentage of the water is actually lost from the groundwater system. In most cases, it is assumed that abstractions are 100% consumptive, and therefore that no groundwater is returned to the system after use. However, in the case of sand extraction operations, the water is often used for conveying sand (in a slurry) within the site or for washing the product. In both cases, the sand is allowed to drain before it leaves the premises with the drained water returning to groundwater.

With regard to the large abstraction at Fourways Quarry, the percentage consumptive use assumed by the Agency for licensing purposes (5%, Steve Kelly, Licensing Officer, Warrington, pers, comm. 2003) has been used in the water balance calculation. A similar approach has been used for the Relick's Moss abstraction, although the recent returns have been only a small percentage of the licensed amount.

[1] The Oakmere piezometers were purged for water quality sampling purposes immediately prior to the field falling head tests.

Table 3.4 Details of groundwater abstraction licences

EA ref.	Location	Grid reference	Use	Licensed for (Ml/a)	Licence return (Ml/a)
256800 1172	Delamere Golf Club *	SJ561702	Golf course irrigation	1	1.44
256800 1001	Quarry at Relick's Moss	SJ564697	Washing	1037	81.9
256800 1251	Pigwood, Fishpool Road	SJ571675	General agriculture	0.23	No return
256800 1200	Lagoon at Fourways Quarry	SJ572685	Agricultural irrigation	26	5.7
256800 1174	Fourways Quarry	SJ575695	Conveying materials	3818	2818
256800 1005	Well at Daleford Farm	SJ605696	General agriculture	5	No return
256800 1225	Daleford Farm	SJ603698	Agricultural irrigation	19	4.4
256800 1227	Daleford Farm	SJ605694	Agricultural irrigation	19	<3
256800 1119	Nova Scotia Farm	SJ613685	General agriculture	0	<3
256800 1210	Daleford Farm	SJ608691	Agricultural irrigation	9	4.75
256800 1181	Common Farm, Whitegate	SJ608681	Agricultural irrigation	5	4.52
256800 1018	Sandiway Golf Club *	SJ619702	Golf course irrigation	2	2.2
256800 1028	Vale Royal Golf Club *	SJ633701	Golf course irrigation	28	13.6
256800 1139	Brook House Farm	SJ636678	General agriculture	6	2.9
New **	Crown Farm Quarry	SJ573703	Dust suppression	279	258
None	FE Nunsmere	SJ588687	Irrigation	30	29.7
None	FE Lob Slack	SJ583702	Irrigation	45	16.5

** Surface water abstraction*
*** Based on returns data from previous licence.*

Returns data are not required for the smaller abstractions of less than 20 m^3/d (7.3 Ml/a) unless they are for spray irrigation. It has been assumed in the water balance calculation that these small licences are abstracting their total licensed amount. It should also be noted that abstractions for domestic use of less than 20 m^3/d (7.3 Ml/a) do not require a licence.

There are two Crown-exempt abstractions on the sandsheet used by Forest Enterprise. Returns data shows that a peak of 46 Ml was abstracted under these licences during 1995. The shadow licences issued by the Agency are for 75 Ml/a.

3.2.2 Natural discharge

Baseflow to surface water streams

There are no permanent surface water discharge gauging facilities on the streams running across and off the sandsheet. In order to quantify the amount of groundwater discharge as baseflow to these streams, a campaign of monthly spot-gauging of discharge was initiated in September 2001. The locations at which this spot-gauging has been carried out (Figure 3.10) are as close as possible to where each stream leaves the outcrop of the sandsheet. Spot-gauging data was available for between September 2001 and September 2002 for the current project.

Spot-gauging at various points (Figure 3.10) along streams was carried out in October 2002, in order both to gauge previously ungauged streams and to characterise the linear distribution of flow accretion through groundwater discharge.

The estimated groundwater catchment areas for the various streams draining the sandsheet are shown on Figure 3.10. On closer inspection of the stream network in relation to the sandsheet, it was found that only the upper section of Sandyford Brook (Sandyford Brook #1) had not been gauged by the Agency. In order to estimate a discharge figure for this sub-catchment, an empirical relationship between the discharge of the gauged catchments and their area was developed. This relationship was used with the area of the Sandyford Brook #2 sub-catchment to estimate its discharge.

The discharge totals for the September 2001 to September 2002 period for each of the stream catchments are presented in Table 3.5. It should be noted that for those marked 'recurrent', the monthly discharge figures have been used to calculate the total discharge. For those marked 'accretion', the single value gained during October 2002 has been multiplied up to arrive at an estimate of total discharge.

Table 3.5 Measurements of groundwater discharge as baseflow to streams

Catchment	Gauging	Total discharge (Ml), 2001-2
Fir/Cuddington Brook	Recurrent	4783
Trib. of Handforth Brook	Accretion	12
Bogart Brook	Recurrent	4341
Shay's Lane/Chester Lane Brook	Recurrent/accretion	1803
Budworth Brook	Recurrent	966
Sandyford #1	Accretion	34
Sandyford #1	By calculation	960

Discharge to the Sherwood Sandstone

For around 4 km along its western edge, the Delamere sandsheet overlies the subcrop of the Sherwood sandstone. Groundwater levels in the sandsheet (c. 73 maOD) and in the Sherwood Sandstone (c. 46 maOD) indicate the potential for groundwater discharge from the former to the latter, and a local hydraulic gradient within the sandsheet towards its western edge confirms that this is an active process.

In order to estimate the discharge from the sandsheet to the Sherwood Sandstone a simple Darcy's Law calculation has been carried out:

$Q = K \times dh/dl \times A$

$= 2.8 \times 0.0053 \times 80000$

$= 1187\ m^3/d$ (434 Ml/a)

where;

K = average hydraulic conductivity from the field hydraulic tests on the Agency piezometers adjacent to Oakmere (2.8 m/d);
dh/dl = calculated from available groundwater level monitoring (i.e., Agency piezometers and Cherry Orchard quarry piezometers);
A = assumed saturated thickness (20 m) multiplied by the length of the strip of sandsheet overlying the subcrop of the sandstone (4 km).

It should be noted that the values used in the calculation are based on measurements in the Oakmere area, and therefore that their extension to represent the whole of the area over which groundwater from the sandsheet discharges to the Sherwood Sandstone is somewhat uncertain. It is therefore sensible to attach a confidence limit of ±10-15% on the estimate for discharge to the Sherwood Sandstone.

Even if the uncertainty in this estimate for the discharge of the sandsheet to the Sherwood Sandstone is taken into account, it is still less than one quarter of the 1800 Ml/a reported by Earp and Taylor (1986). The latter figure was based on regional groundwater flow modelling by the North West Water Authority.

Diffuse discharge at the edge of the sandsheet

It is likely that a small proportion of groundwater from the sandsheet discharges around its edge at the surface contact with the Upper Boulder Clay. It is likely that any zones of this type of discharge are marked by areas of damp ground conditions, and that the discharge is effected by locally enhanced evapotranspiration rather than surface runoff. No such areas were identified during visits to the area.

Earp and Taylor (1986) note that the base of glacial sands overlying the Lower Boulder Clay is marked in places within the Weaver valley by a seepage line. Figure 2.4 shows that towards its north-east margin the outcrop of the sandsheet comes within a few hundred metres of the Weaver valley, and that the sands are also mapped as outcropping in the valley. It is thought likely that a seepage line marking groundwater discharge from the sandsheet exists along this reach of the Weaver valley, although this has not been confirmed in the field.

Downwards flow into the Mercia Mudstone formation

The majority of the Delamere sandsheet is underlain by the Northwich Halite unit of the Mercia Mudstone Group formation. This unit is mainly composed of mudstones and siltstones and is therefore assumed to have negligible permeability compared to the sandsheet. The results of numerous pumping tests in the Mercia Mudstone Group of the South Cheshire Basin are reported in the Aquifer Properties Manual (BGS, 2000). The geometric mean of reported transmissivity values is 23.6 m^2/d. Clearly, the reported transmissivities are a function of the depth of the tested boreholes, but if a saturated thickness of around 200 m is assumed, this equates to a hydraulic conductivity of around 0.1 m/d. The following observations can be made on this value:

1) The tests for which results were reported were likely to have been performed in locations where the Mercia Mudstone was expected to have a reasonable water supply potential. They will therefore be biased towards the potential of the formation as an aquifer rather than its properties as an aquitard.

2) The reported values will reflect the horizontal hydraulic conductivity of this highly layered formation, but it is the vertical hydraulic conductivity which will control downwards leakage from the Delamere sandsheet.

From the above argument it seems likely that the vertical hydraulic conductivity will be orders of magnitude less than the 0.1 m/d derived from reported aquifer test results. It has therefore been assumed that downwards flow of groundwater from the sandsheet into the Mercia Mudstone formation is negligible.

3.3 Hydrochemistry

Savage *et al* (1993) detail clear evidence which shows that the waters of Oakmere have varied between acid base-poor and moderately base-rich, although the latter condition is thought to have been caused by pumping of groundwater into the lake. In general, it is found that base-poor conditions are observed when the lake level is rising, and that relatively base-rich conditions occur when the lake level is falling or when it is at a low level for a long period of time (e.g. 1974, 1977, 1989-90)

Water quality samples were taken from the Agency piezometers adjacent to Oakmere and Abbots Moss (but not from surface waters in the cSACs) during November 2002. The pH was lowest in the piezometers closest to the surface water features in Oakmere and Abbots Moss.

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Figure 3.1 Location of boreholes for which groundwater levels were available

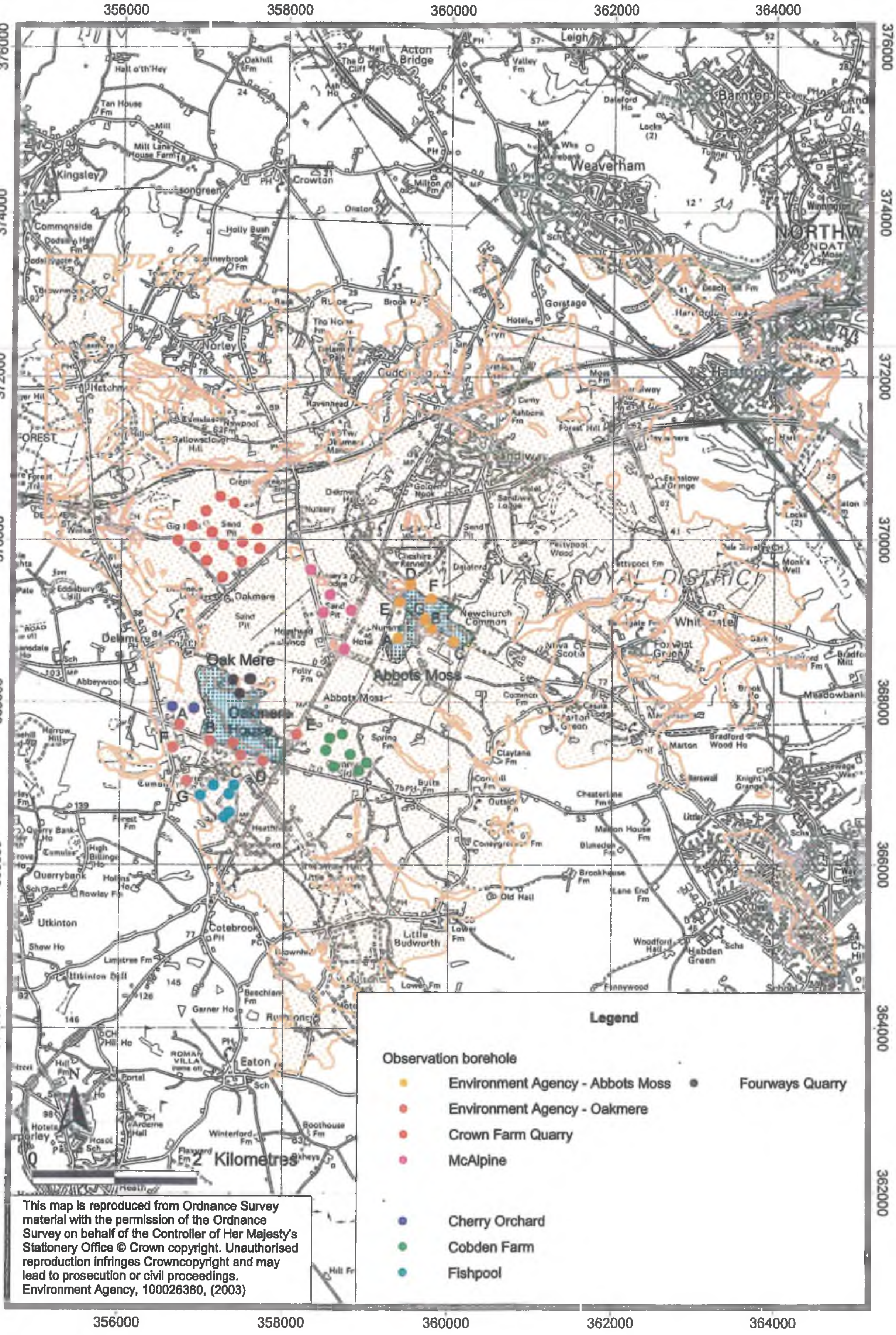

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Figure 3.2 Composite groundwater level hydrograph

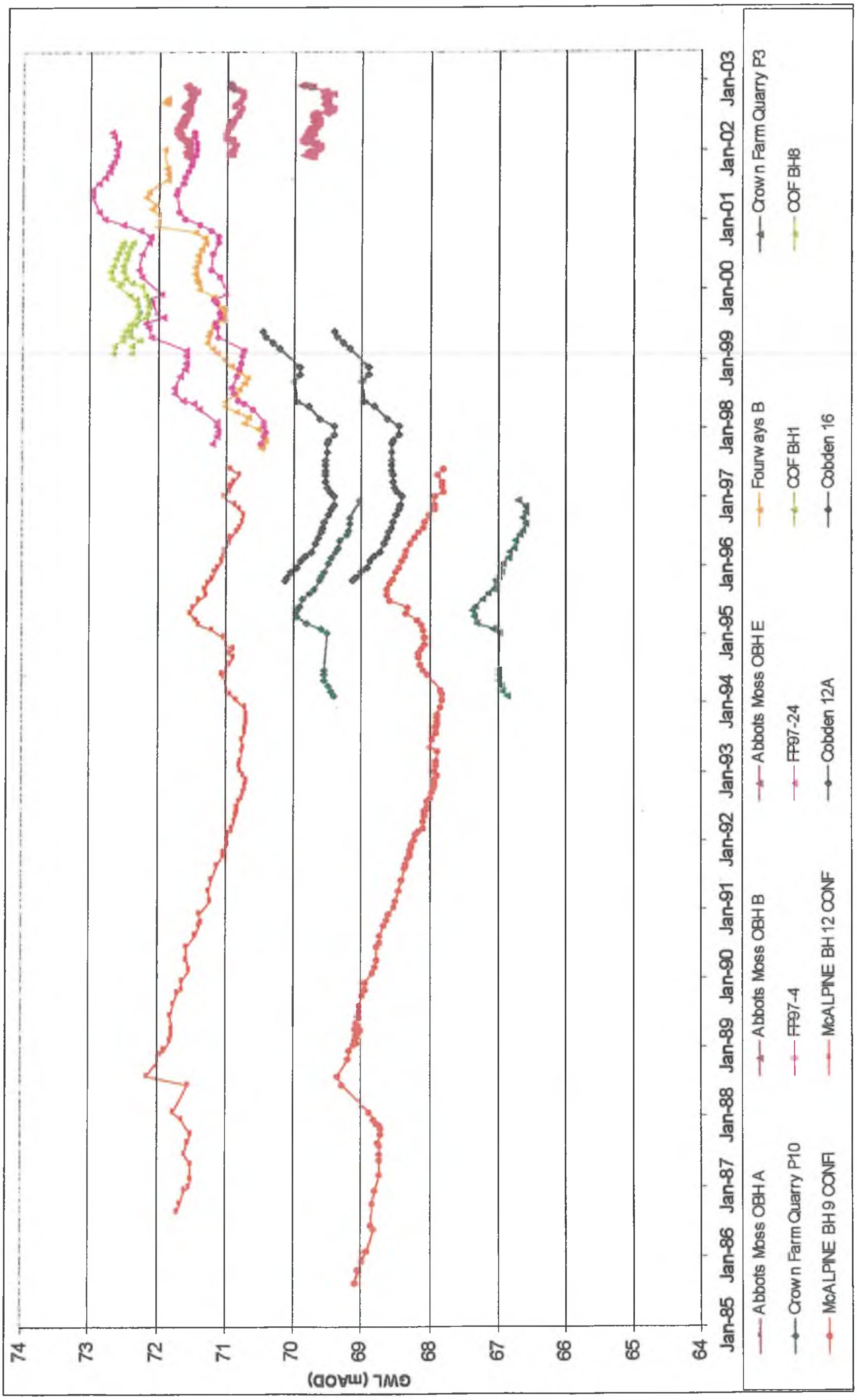

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Figure 3.4 Groundwater level hydrograph for the Agency Oakmere piezometers

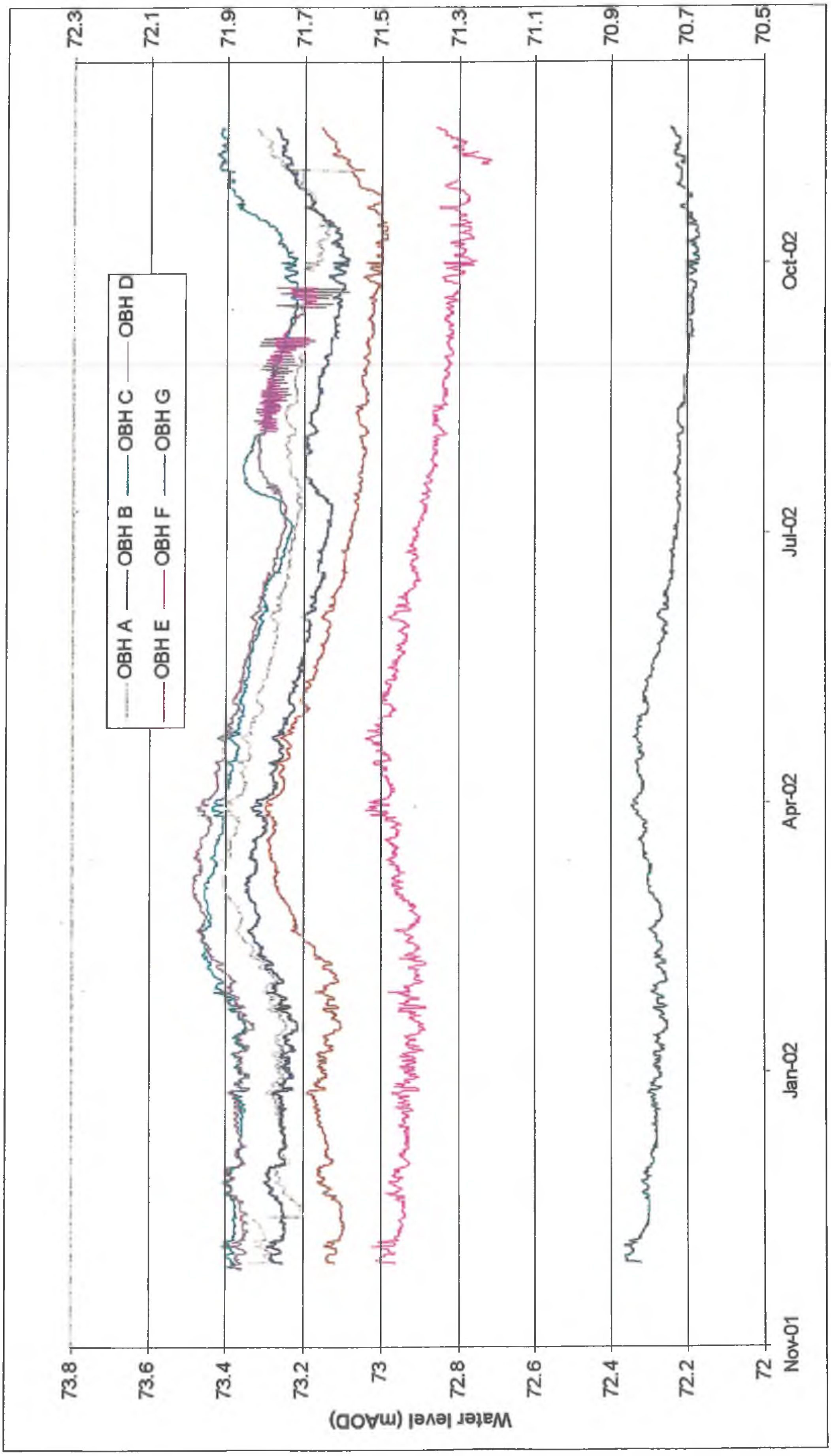

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Figure 3.3 Groundwater contour map

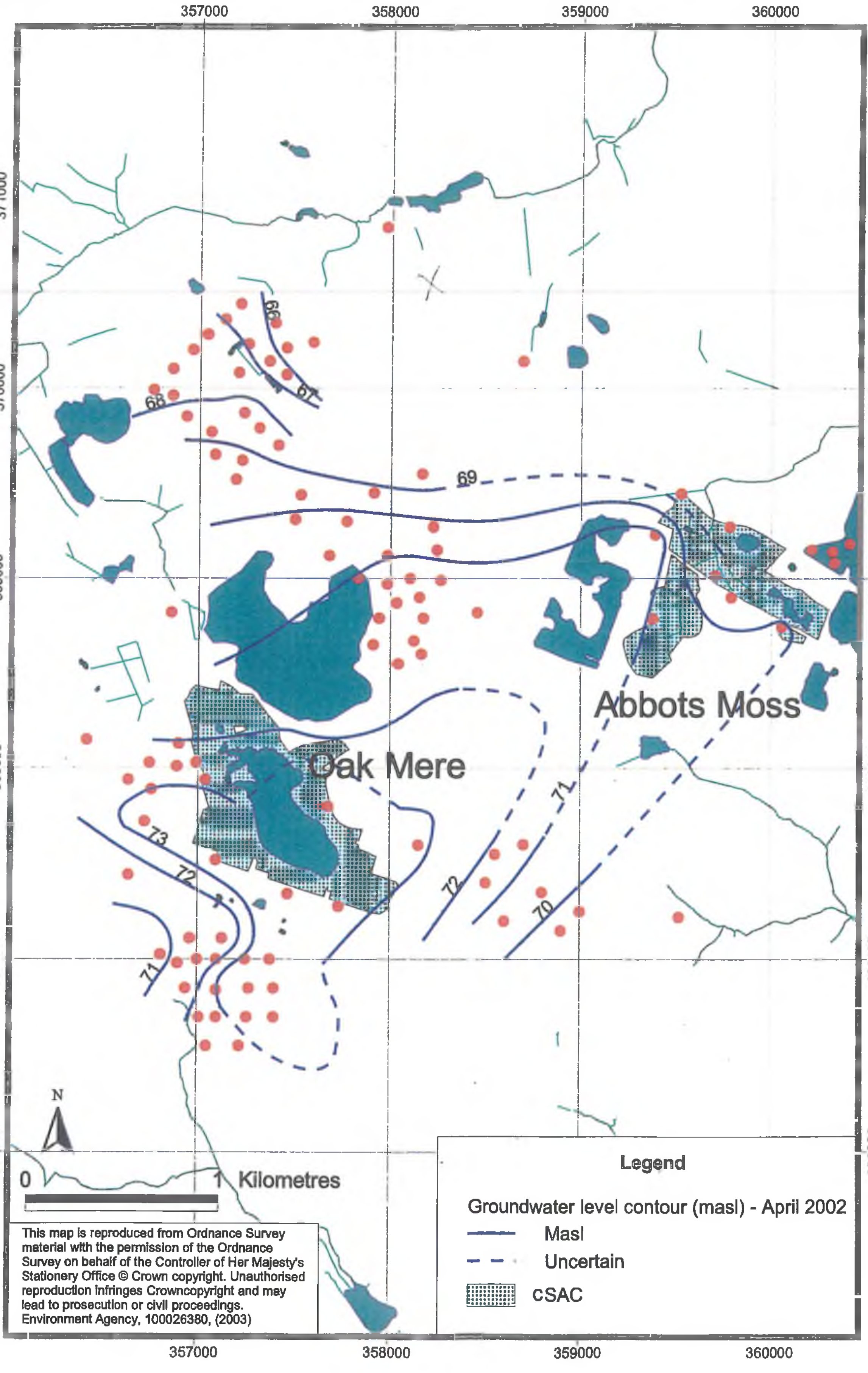

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Figure 3.5 Groundwater level hydrograph for the Agency Abbots Moss piezometers

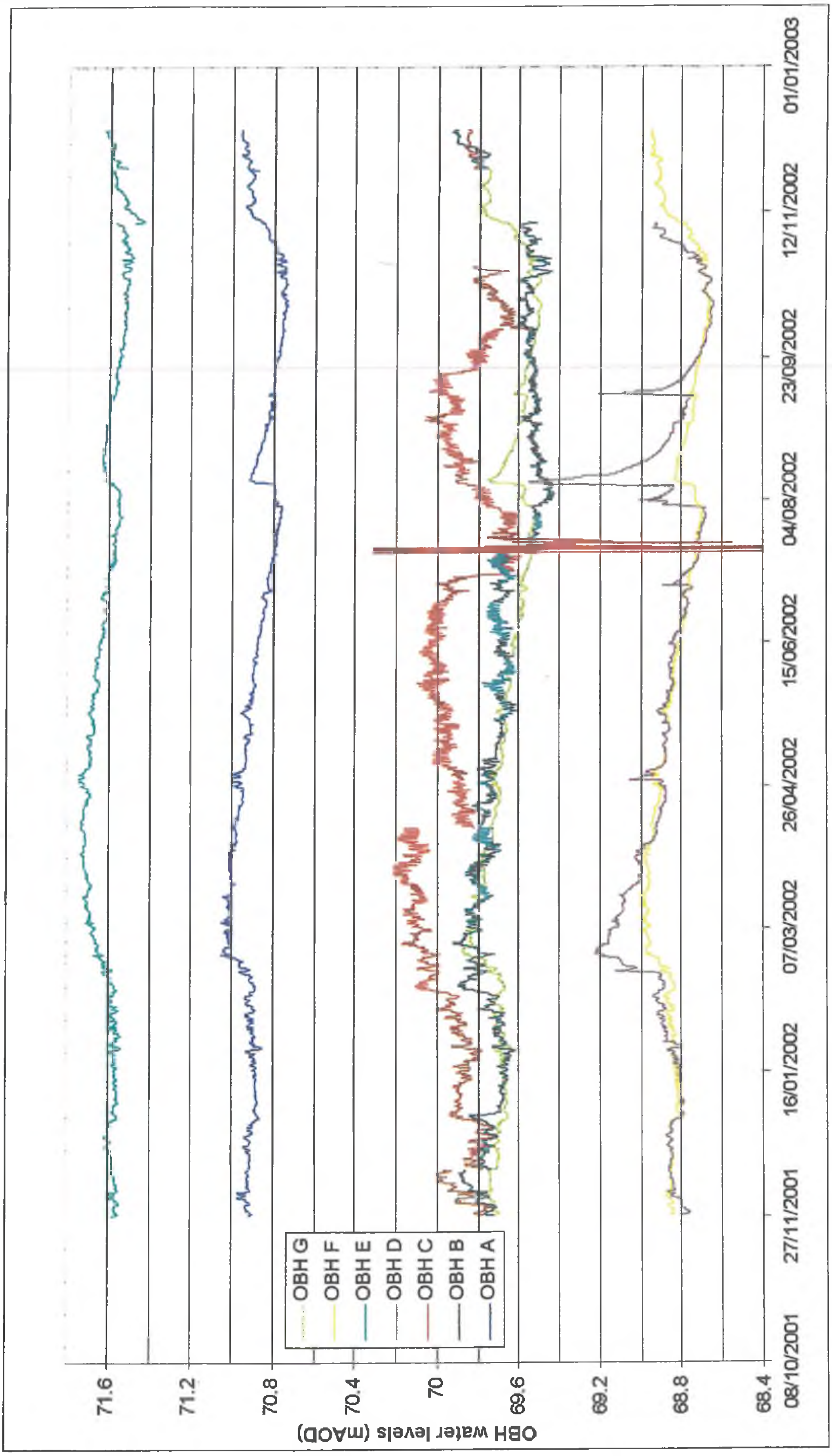

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Figure 3.6 Comparison of Oakmere lake level and regional groundwater levels

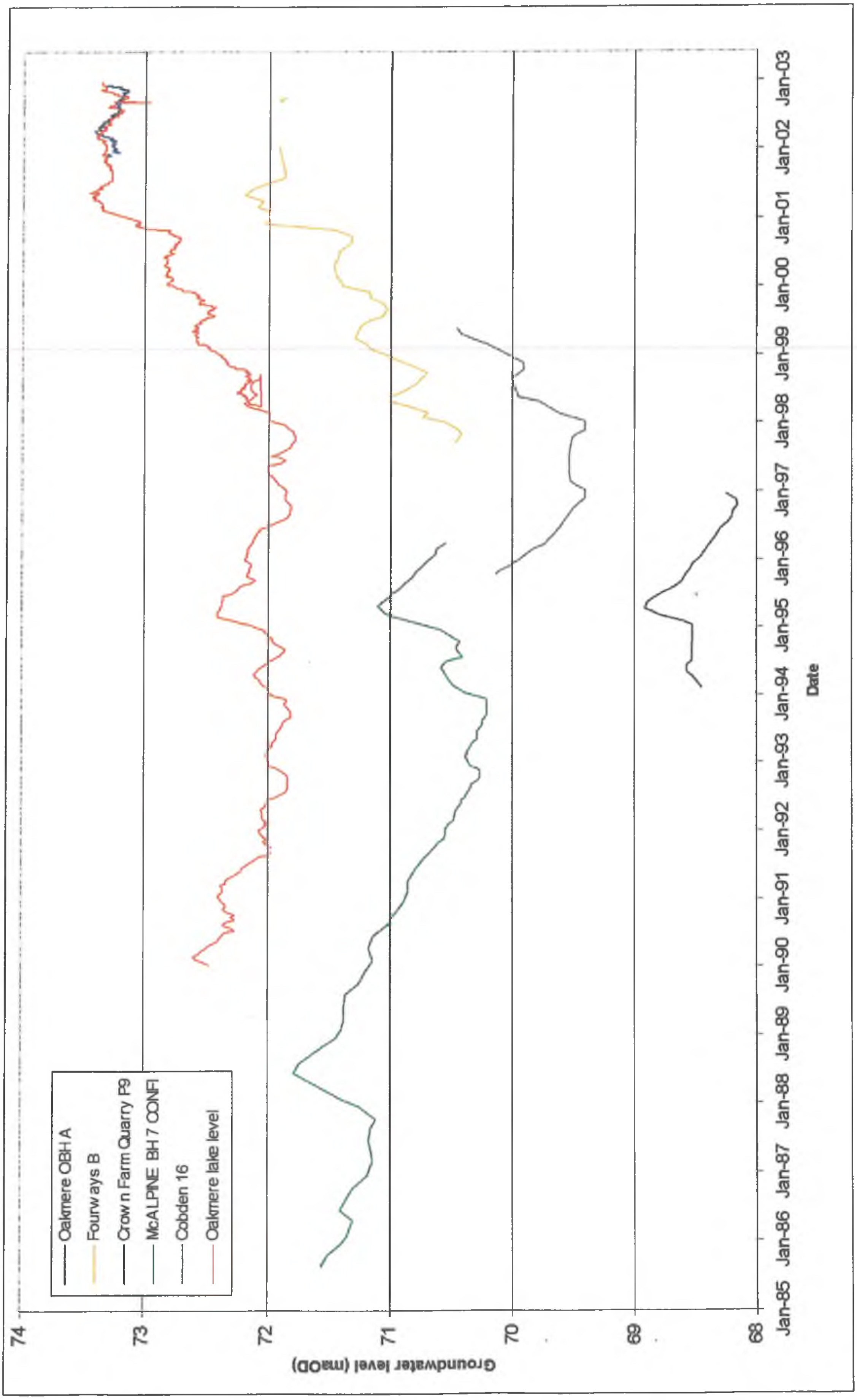

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Figure 3.7 Comparison of Oakmere lake level with the Agency Oakmere piezometer B & C, 2001-2002

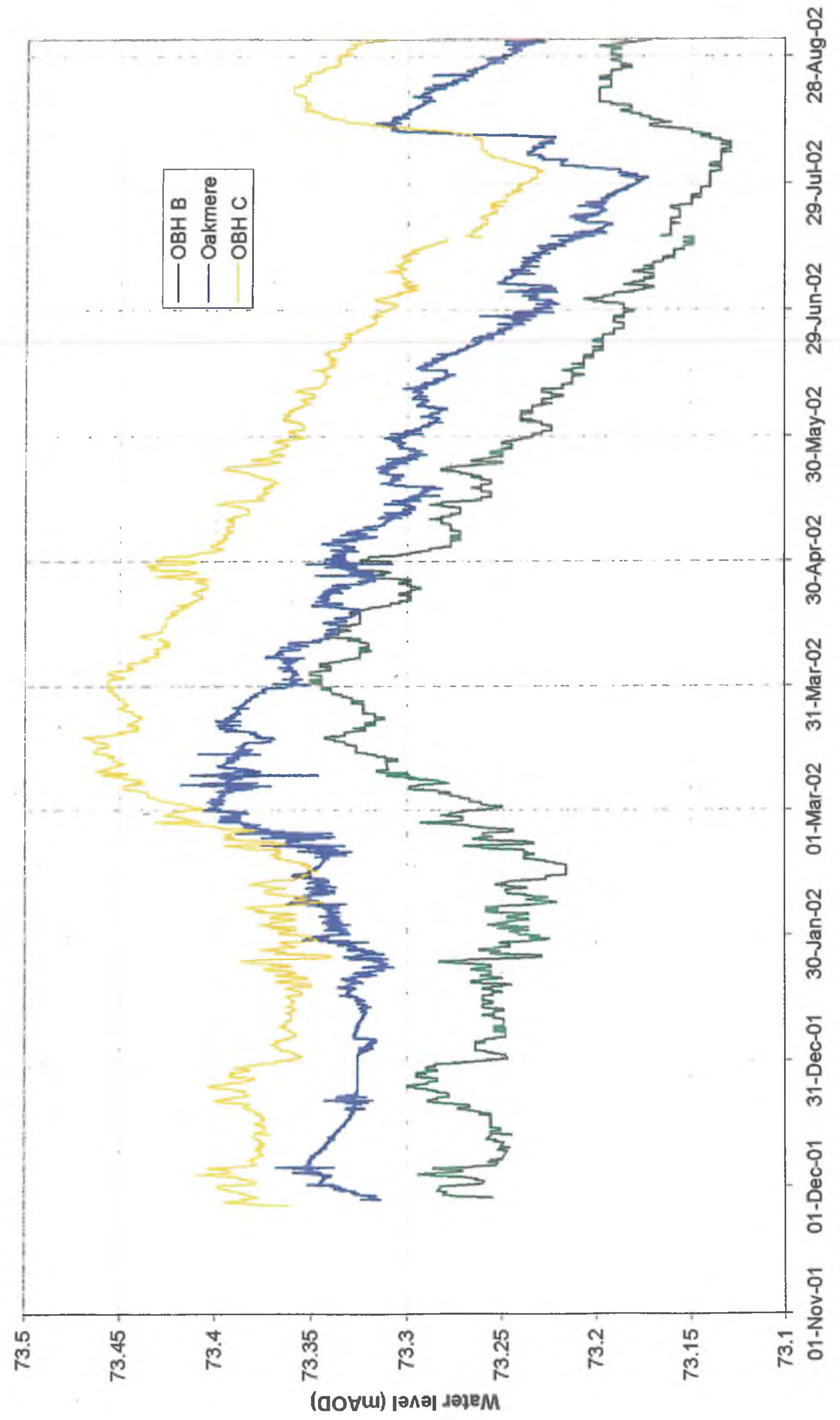

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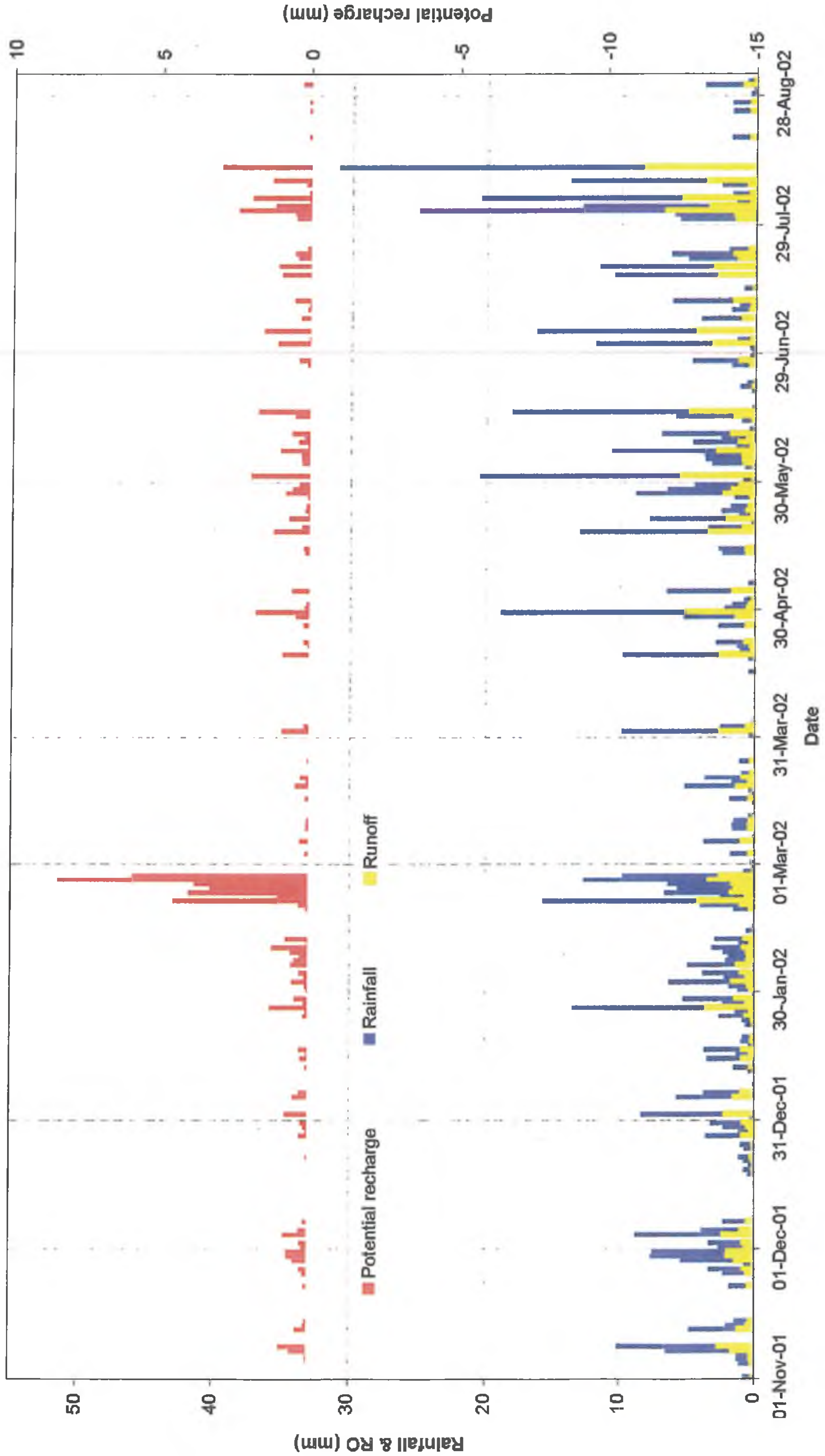
Figure 3.8 Rainfall and estimated recharge for the Delamere area (1 November 2001 to 28 August 2002)



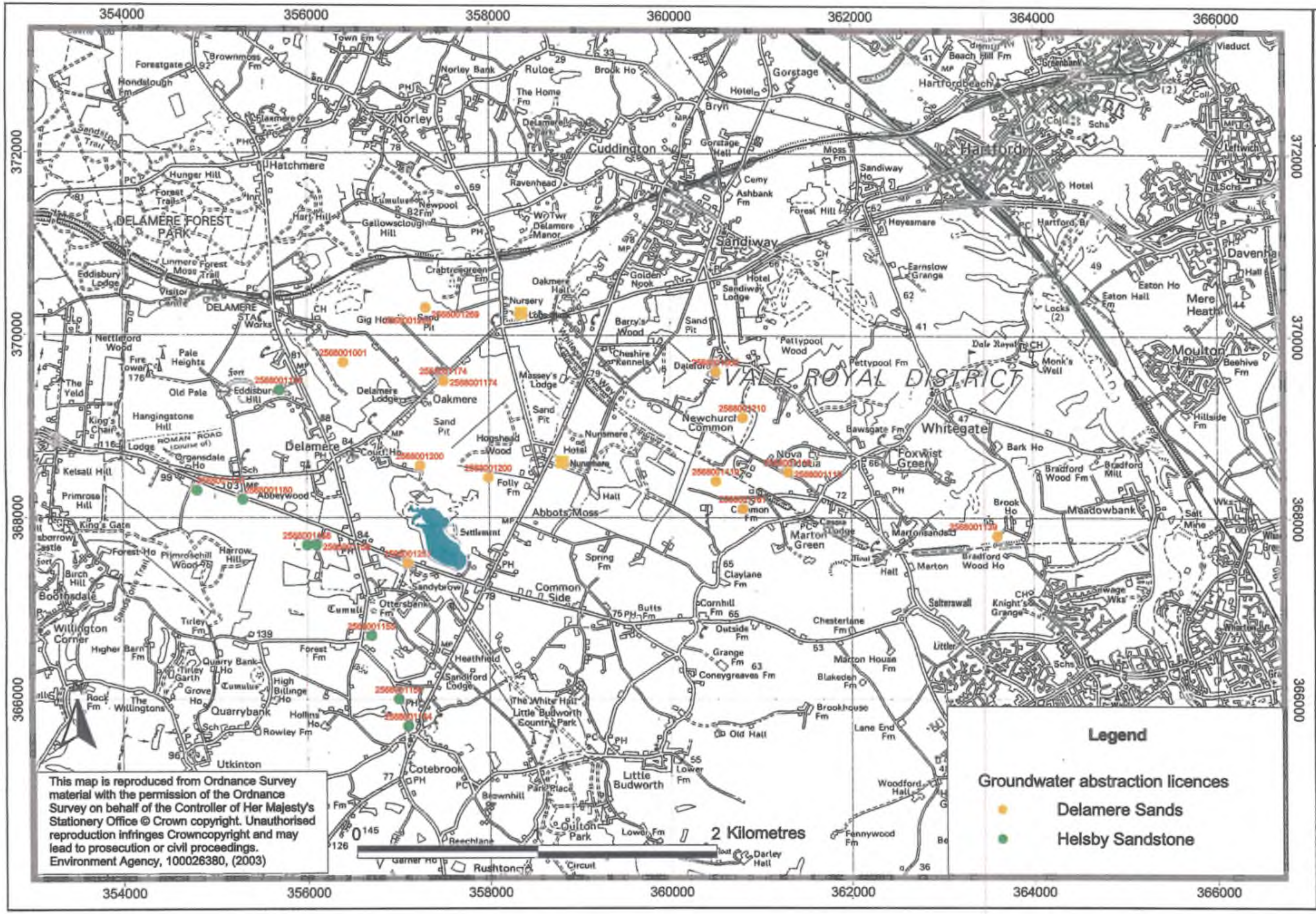


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Figure 3.9 Location of licensed groundwater abstractions

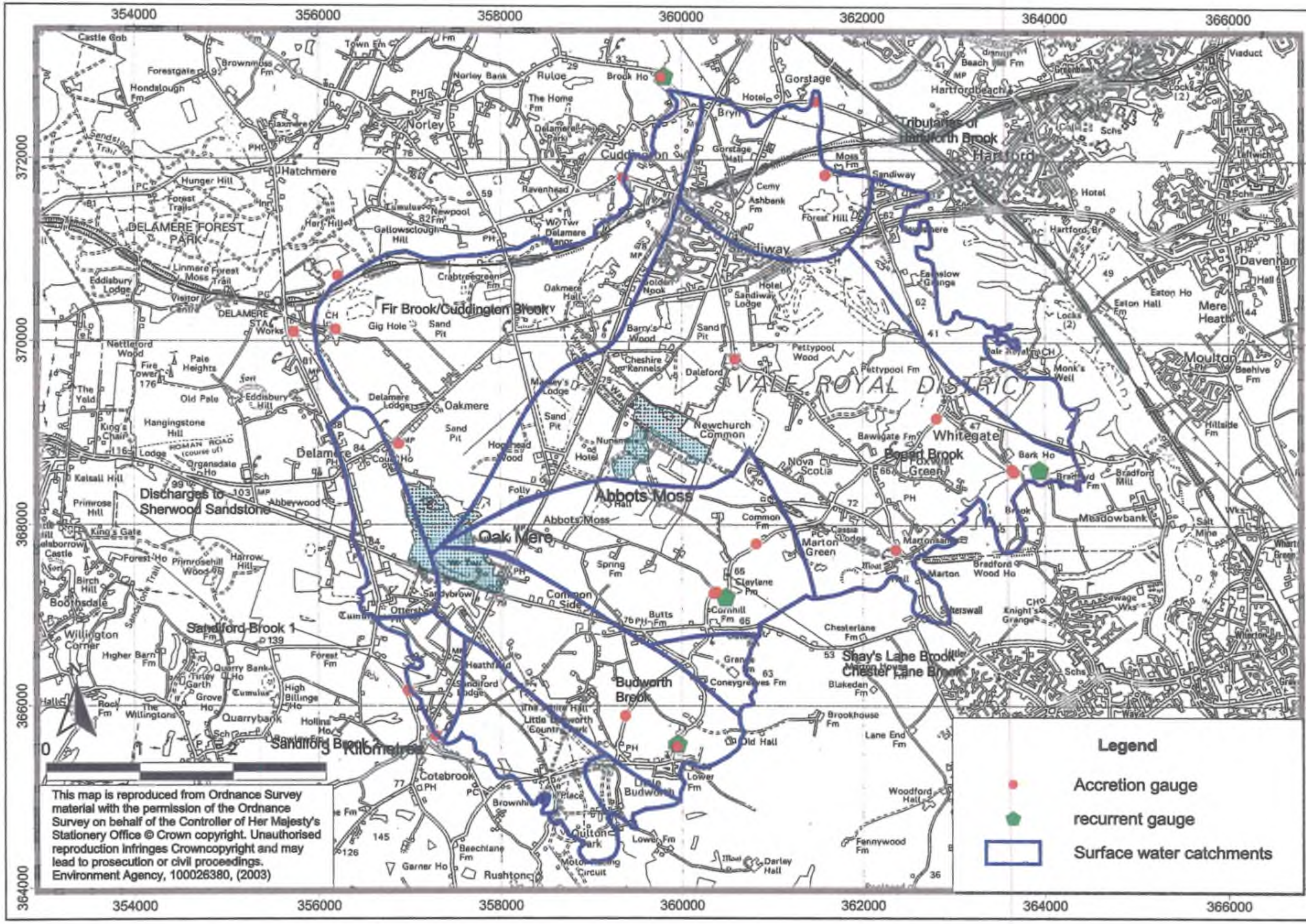

Figure 3.10 Stream gauging locations and groundwater catchments

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4 WATER BALANCE CALCULATIONS

4.1 Spatial and temporal limits for the water balance calculation

4.1.1 Identification of a hydrogeologically-discrete study area

In order to develop a groundwater balance for the sandsheet, it was first necessary to define a discrete volume of aquifer for which recharge, discharge and changes in storage could best be quantified. The plan outline of this volume is referred to hereafter as the study area.

As discussed in Section 3.2.2, it is assumed that the Mercia Mudstone formation underlying the sandsheet has an extremely low hydraulic conductivity, and therefore that groundwater flow from the sandsheet downwards into this formation is negligible.

The western boundary of the study area was taken as the line of contact between the sandsheet and the Sherwood Sandstone (mid-Cheshire ridge) (Figure 4.1).

The southern and south-eastern boundaries to the study area were taken as the line of contact between the sandsheet and the Upper Boulder Clay (Figure 4.1). Although it is known that the sands continue beneath the cover of Upper Boulder Clay in many areas, it is assumed that they pinch out within this unit a relatively short distance from the contact (see Section 2.1.2). Hence, it is assumed that groundwater from the sandsheet will discharge along the line of contact.

The western and north-western boundaries of the study area were also taken as the line of contact between the sandsheet and the Upper Boulder Clay (Figure 4.2).

The northern boundary has been placed along the Fir Brook/Cuddington Brook. This valley is deeply incised into the sandsheet to the extent that it is almost certain that all groundwater flowing northwards within the sandsheet discharges to the brook as baseflow. Earp & Taylor (1986) also report a clay layer outcropping at the base of the valley which will restrict any deeper groundwater circulation in this area.

4.1.2 Historical time period for water balance calculations

Useful water balances can be prepared only for historical periods for which data exists for all of the main components. The limiting factor in this regard for the Delamere sandsheet is the availability of baseflow spot-gauging of the streams draining the sandsheet. The aggregate discharge from these sources represents a large part (80-90%) of groundwater discharge within the study area, and it is therefore a key component of the water balance. Spot-gauging of the streams was initiated in September 2001 by the Agency and data up to October 2002 has been available for the current project. This period was adopted for the water balance calculations.

4.2 Recharge estimation

4.2.1 Method

Recharge was calculated using the FAO-based (FAO, 1998) methodology developed by the Agency (Hulme *et al*, 2001, EA, 2002). This methodology is based on a soil moisture calculation, but it allows a more detailed consideration of the space- and time-variance of crop and soil water properties. It is therefore thought to allow a more accurate calculation of recharge than approaches used previously, such as the Penman-Grindley algorithm. A detailed description of the FAO-based methodology is not given here and interested parties are directed to the references given above. A description of the sources of data and any data processing is given below.

4.2.2 Rainfall

Five rainfall stations were identified within 5 km of the sandsheet (Table 4.1). For each day during the period 1982-2002, the mean rainfall at these five stations was calculated, and the resulting annual average was also calculated. The mean daily rainfall figures were then factored such that the long-term average rainfall was the same as the long-term average rainfall for the Delamere area (840 mm/a) as calculated by the Meteorological Office.

Table 4.1 Rainfall stations located within 5 km of the Delamere sandsheet

Name	NGR	Period of record
Delamere Forest	SJ529713	1990 – 1996
Oakmere House	SD577675	2002
Mouldsworth	SJ503704	1961 –Present
Eddisbury Fruit Farm	SJ534702	1963 –Present
Delamere PS	SJ560677	1974 –Present

4.2.3 Potential evaporation

Weekly potential evaporation estimates (MORECS: grid square 109) were available only for the period January 1982 to March 2002. In order to extend this dataset to September 2002, the average weekly potential evaporation for the March to September period between 1982 and 2001 was used. Data was converted from weekly to daily for the recharge calculation.

4.2.4 Land use and soil type

Hydrological soil property information (e.g., field capacity, wilting point) for soils was taken from an Agency database developed using data leased from the National Soil Resources Institute (NSRI). Information is provided on a '1km grid', with the properties of the dominant soil type in each square reported. The four main soil types which occur over the Delamere sandsheet are detailed in Table 4.2.

Table 4.2 Soil types on the Delamere sandsheet

Name	Description
Crannymoor	Deep well drained sandy soil associated with glaciofluvial drift. It is the dominant soil type for the majority of the grid squares in the Delamere area
Newport	Deep well drained sandy and coarse loamy soils associated with glaciofluvial drift. Most dominant in the eastern parts of the study area.
Bridgnorth	Well drained sandy and coarse loamy soils over soft sandstone. Found over the Sherwood sandstone on the western edge of the study area
Salop	Slowly permeable seasonally waterlogged reddish fine loamy over clayey fine loamy and clayey soils. Only dominant in a small area to the south of Budworth pool.

4.2.5 Results

For the 1982-2002 period, the estimated average annual recharge to the sandsheet was 339 mm, representing 39.6% of the average rainfall. This is a relatively high percentage which is most likely to be explained by the sandy, high permeability soils over the sandsheet.

Further discussion of the recharge estimation calculations is included in Section 4.4.

4.3 Change in groundwater storage

Detailed inspection of relevant groundwater hydrographs showed that groundwater levels were universally lower in September 2002 than in September 2001. The fall in levels varied between monitoring boreholes and ranged between 5 and 21 cm. The average fall in levels over the sandsheet was judged to be around 14 cm. Assuming a drainable porosity of 25% for fine to medium sand (Domenico and Schwartz, 1990), this fall in groundwater levels over the study area equates to a release of storage of 1,389 Ml/a.

4.4 Water balance calculation

The results of the water balance calculations are presented in Table 4.3. For the September 2001 to September 2002 period, for which measurements of groundwater discharge through baseflow to streams was available, there is an out-of-balance of –11%, meaning that 11% more groundwater has been estimated to have left the sandsheet than was estimated to have been added. This out-of-balance is of a size which could easily be explained by errors in the measurement or estimation of the various groundwater discharge components, and it is therefore assumed that no significant components have been omitted from the water balance calculation.

The fact that the groundwater balance for the sandsheet has been closed within the error associated with measurement or estimation of the various component flows offers considerable support for the conceptual understanding of the hydrogeology of the sandsheet developed during the project.

Table 4.3 Water balance calculation results

	2001-2002	
	Ml/a	**% of recharge & storage release**
Recharge (39.68 km^2)	+11242 (283 mm)	
Change in storage	+1389*	
Abstractions (Quarries 5% consumptive)	-485	-4%
Seepage to west into SSG	-434	-3%
Stream baseflow discharge	-12899	-102%
Open water evaporation (passive abstraction from quarry lakes)	-190	-2%
Balance	**-1377**	**-11%**

* a fall in groundwater levels during 2001-2 caused a release of groundwater storage

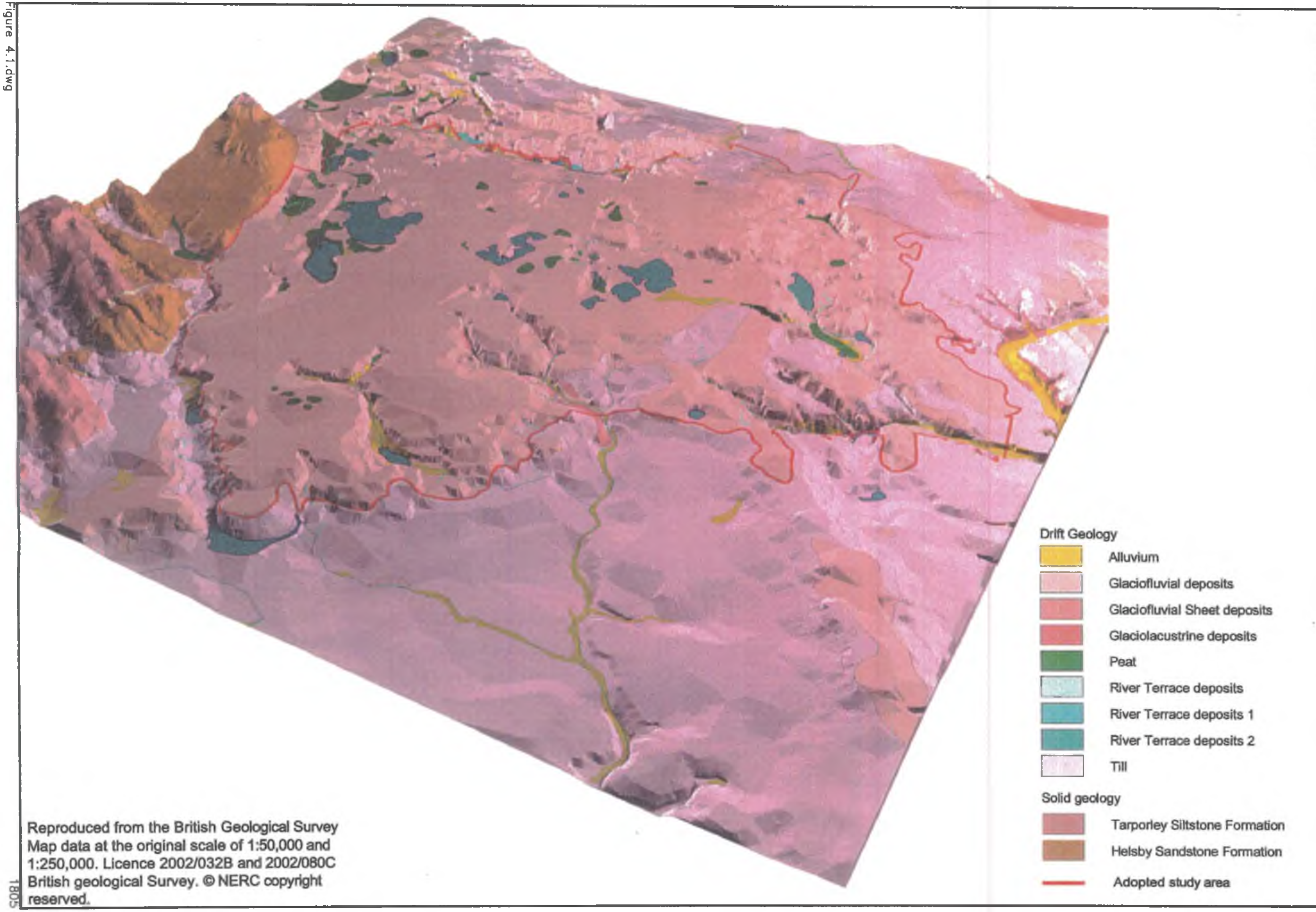

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Figure 4.1 3D visualisation with 'draped' geology and adopted study area (from south)

Figure 4.1.dwg

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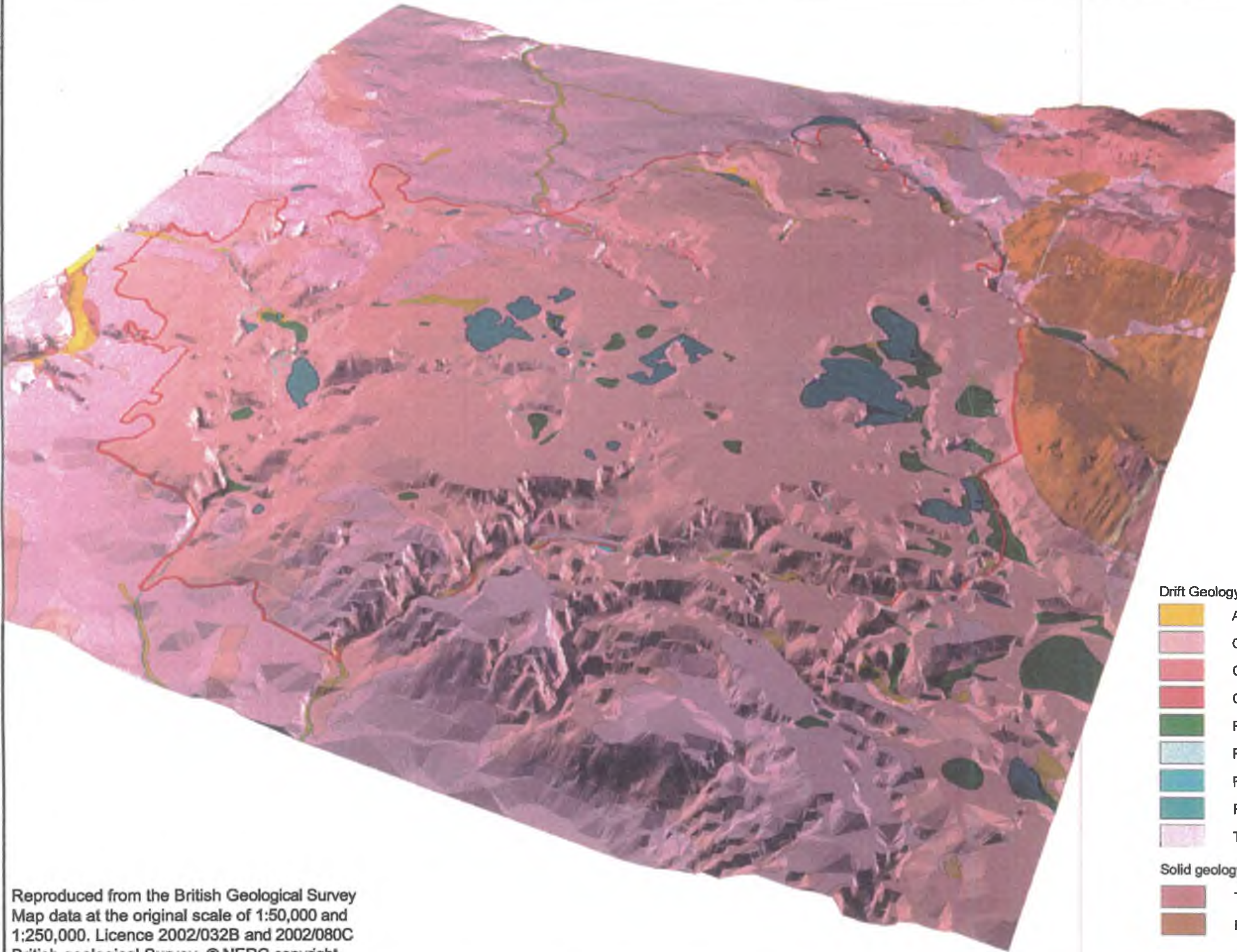

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Figure 4.2 3D visualisation with 'draped' geology and adopted study area (from north)

Figure 4.2.dwg

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5 HYDROGEOLOGICAL CONCEPTUAL MODEL

5.1 General hydrogeology

5.1.1 Lithology and aquifer properties

The Delamere sandsheet is a fluvioglacial deposit comprising mainly sand with additional much smaller components of both clay and gravel. The sand component is homogeneous over vertical intervals of up to 10 m, and it is probably laterally homogeneous over many hundreds of metres. The clay component is found in horizontal bands which vary in thickness between a few centimetres and about one metre. The majority of these clay bands appear to be laterally persistent over only a few hundred meters, although the thicker ones are generally more persistent. For example, a 1 m thick, laterally extensive, clay band has been identified at an elevation of 50 maOD within the sandsheet.

The hydraulic conductivity of the fine to medium sands encountered in the Oakmere and Abbots Moss areas has been determined to be around 3 m/d during the current project. The hydraulic conductivity of the clay layers has not been determined, but it is likely to be of the order of 10^{-5} m/d (Domenico and Schwartz, 1990).

The presence of the horizontal clay bands has a fundamental influence on the hydraulic conductivity of the sandsheet. On a scale much smaller than that of the characteristic lateral extent of the clay bands (e.g., at any one point over the sandsheet), they cause the vertical hydraulic conductivity of the deposit to be many orders of magnitude lower than the horizontal hydraulic conductivity. At a scale larger than that of the characteristic lateral extent of the clay bands, their influence on the vertical hydraulic conductivity will be reduced. Hence, whilst the vertical hydraulic conductivity will still be less than the horizontal hydraulic conductivity, their values will be much closer.

The majority of the Delamere sandsheet rests on a subcrop of the Northwich Halite (Mercia Mudstone Group). The vertical hydraulic conductivity of this formation is of the order of 10^{-3} m/d. A narrow strip (c. 500 m) of the sandsheet along its western edge rests on a subcrop of the Helsby Sandstone (Sherwood Sandstone Group). The hydraulic conductivity of this formation is of the order of 1.0 m/d.

5.1.2 Groundwater recharge and groundwater flow

Rainfall-derived recharge occurs over the whole of the sandsheet. The estimated average recharge for the period 1982-2002 is 339 mm/a which equates to around 40% of rainfall.

Groundwater flow within the sandsheet, to a first approximation, can be considered to be radial. A high point in groundwater levels exists in the vicinity of the southern portion of Oakmere and groundwater levels fall in all directions from this. The hydraulic gradient at any point within the sandsheet appears to be a function of its proximity to a groundwater discharge zone. Hence, in the centre of the sandsheet, at a maximum distance from the groundwater discharge zones within the deeply incised stream valleys, hydraulic gradients are relatively low. Close to groundwater discharge points, for example stream valleys or the edge of the sandsheet, hydraulic gradients are much higher. It is thought that this water table profile is caused by horizontal hydraulic conductivity being much higher than vertical hydraulic conductivity within the sandsheet.

Another effect of the contrast between vertical and horizontal hydraulic conductivity will be that groundwater flow and circulation will be relatively shallow. It is likely that the base level of significant groundwater flow is coincident with the elevation of the streams draining the sandsheet, and in some areas it could be significantly higher.

5.2 Groundwater discharge from the sandsheet to the Sherwood Sandstone

Figure 5.1 is an east-west hydrogeological cross-section through Oakmere and the mid-Cheshire ridge. From a geological perspective, it shows the exact relationship between the East Delamere Fault, the related subcrops of the Mercia Mudstone and Sherwood Sandstone, and the overlying Delamere sandsheet. With regard to the sandsheet, the presence of horizontal layers of clay and a layer of Lower Boulder Clay should be noted.

From a hydrogeological perspective, Figure 5.1 shows a number of interesting features:

1) A hydraulic gradient from east to west exists within the sandsheet west of the groundwater divide.

2) Groundwater levels within the sandsheet are currently around 25 m higher than those in the Sherwood Sandstone.

3) Groundwater levels are maintained at more than 71 maOD at the extreme western edge of the sandsheet, demonstrating the effect of clay bands within the sandsheet and/or a layer of Lower Boulder Clay in reducing the vertical hydraulic conductivity of the sandsheet.

4) Groundwater discharge from the sandsheet to the Sherwood Sandstone is thought to be concentrated at the extreme western edge of the sandsheet, where the horizontal layers of sand come into direct contact with the subcrop of the Sherwood Sandstone. Discharge over the remainder of the subcrop of the sandstone is severely limited.

5.3 Hydrogeological influences on the Oakmere and Abbots Moss sites

Detailed interpretation of groundwater levels in the vicinity of Oakmere and the surface water level in Oakmere during 2001-2 (Section 3.1.2) has shown that Oakmere is in good hydraulic continuity with the groundwater system. Comparison of longer-term fluctuations of the surface water level with regional fluctuations in groundwater levels has confirmed this interpretation. In simple terms, this means that surface water levels in Oakmere are an expression of the local water table.

Although over the longer-term the level of Oakmere will be the same as that of the surrounding groundwater, short-term differences in level can develop as a result of the higher sensitivity of surface water levels to evaporation or rainfall. During the summer, lake levels fall more rapidly that groundwater levels causing groundwater to flow into the lake. This is probably the explanation for the higher nutrient levels seen during extremely dry periods (Savage *et al*, 1993). Also during the summer, and on a shorter timescale, lake levels will rise as a result of significant rainfall events whilst groundwater levels are unlikely to rise because of limited recharge (because of large soil moisture deficits). Hence, water will flow from the lake to the groundwater system. Such an event was recorded at the start of August 2002 in the piezometers surrounding Oakmere.

Unfortunately, surface water levels within Abbots Moss are not recorded, and therefore their relationship to the surrounding groundwater system has not been established. It is considered unlikely, however, that a significantly different situation to that at Oakmere exists at Abbots Moss, and it is therefore tentatively assumed that Abbots Moss is in hydraulic continuity with the groundwater system.

5.4 Fluctuations in the level of Oakmere over the last 15 years

Some concern has been expressed recently about the significant fluctuations in the level of Oakmere over the last 15 years, with very low levels recorded in 1991-1992 and 1997, and high levels in 2001-present. The conceptual model detailed above is interpreted to explain these fluctuations below.

Oakmere is located in close proximity to a groundwater divide, and in simple terms is close to the top of a mound of groundwater within the Delamere sandsheet. In any groundwater system dependent on areal recharge, groundwater level fluctuations at a groundwater divide (at the 'top' of the system) will be much larger than those at locations close to areas of groundwater discharge (at the 'bottom' of the system). The level of Oakmere is an expression of the water table, and its position on a groundwater divide means that its level is likely to fluctuate significantly.

There has been a recent trend towards increased medium-term climatic variability. This trend started in the late-1980s, after a period of 'average' conditions during the early- and mid-1980s. It then proceeded with a wetter period centred on 1988, a drier period centred on 1990-1991, a wetter period centred on 1995, a drier period centred on 1996-7, and a wetter period centred on 2001. This climatic variability has been reflected in groundwater levels. For example, in many areas the lowest and highest groundwater levels since records began were recorded in late-1997 and mid-2001 respectively.

The combination of Oakmere's location where groundwater level fluctuations will be relatively high, and the increased climatic variability over the last fifteen years causing unprecedented groundwater fluctuations, explains why the level of Oakmere has fluctuated significantly in the recent past.

It should also be recognised that the recent medium-term climatic variability is not unprecedented and numerous episodes of wetter and drier conditions are known to have occurred. It is possible that the ecology of the lakes has developed partly in response to these variations rather than 'average' conditions.

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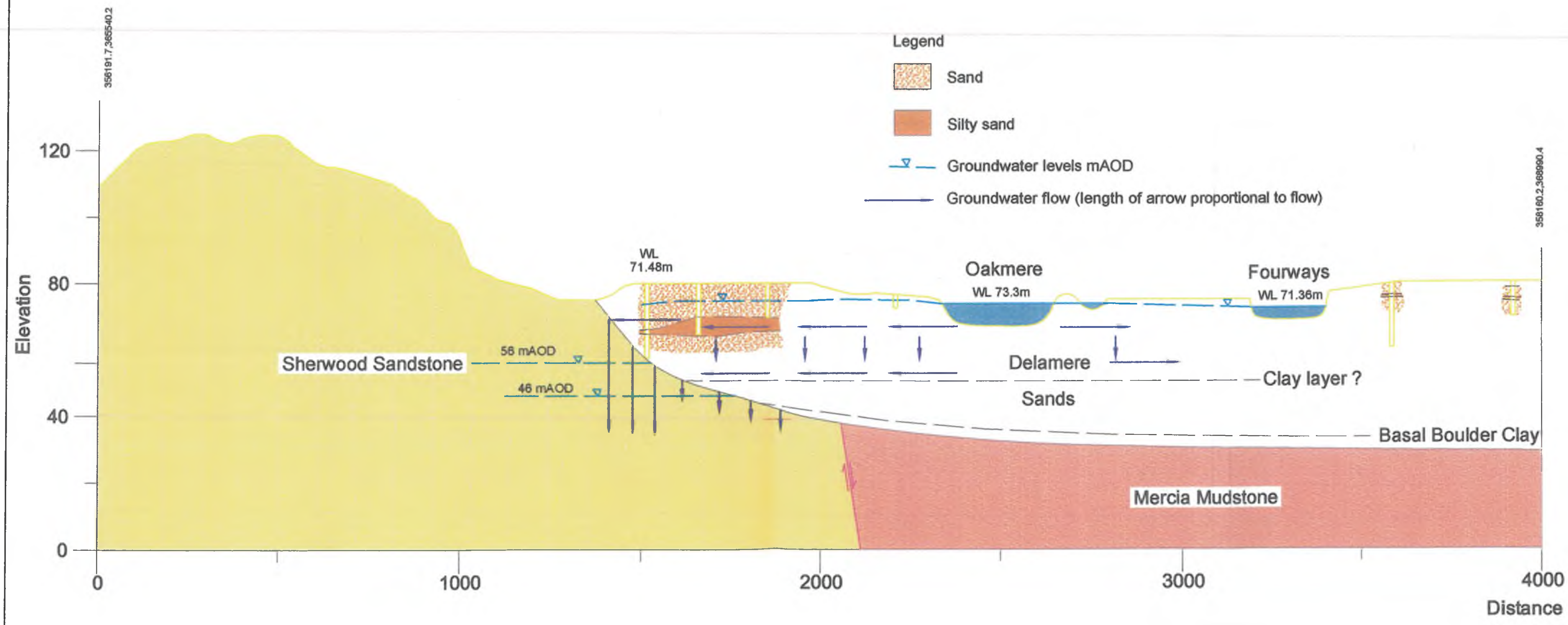
Figure 5.1 Cross section - Oakmere



6 ASSESSMENT OF THE EFFECT OF LICENSED GROUNDWATER ABSTRACTIONS AND OTHER POSSIBLE INFLUENCES

6.1 Groundwater abstractions licensed by the Agency

6.1.1 Groundwater abstraction from the Sherwood Sandstone

Prolonged groundwater abstraction from the Sherwood Sandstone adjacent to the Delamere sandsheet, which commenced in 1905, has caused an artificial groundwater regime to be established in the Delamere area. Prior to the commencement of pumping from the sandstone, groundwater levels within the mid-Cheshire ridge (c. 73 maOD) were at a similar level or perhaps slightly higher than those in the Delamere sandsheet. There is therefore the possibility that groundwater flowed from the former, in an easterly direction, through the Delamere sandsheet and into the River Weaver.

If the groundwater regime suggested above did exist prior to the commencement of pumping from the sandstone, a significant effect of the lowering of groundwater levels through pumping after 1905 would have been a reduction in the (recharge and) groundwater catchment areas for the Oakmere and Abbots Moss cSACs. A direct result of any reduction in groundwater catchment area would have been lower groundwater levels and reduced seasonal and medium-term variability of groundwater levels within the sandsheet. In order to estimate the possible magnitude of these effects it is necessary to estimate the amount by which the groundwater catchment areas of Oakmere and Abbots Moss were reduced when groundwater levels were lowered.

Evidence from which the groundwater regime in the area prior to 1905 can be re-constructed is fairly sparse, and there are certainly insufficient groundwater level measurements with which to develop a sufficiently detailed historical groundwater contour map. Topographic and historical evidence does, however offer some insight into the former regime. The 1:25,000 topographic survey of the area is included as Figure 6.1 and it shows the presence of the Fishpool, a significant topographic low-point on the outcrop of the sandstone approximately 700 m south-west of Oakmere. The elevation of the Fishpool (c. 71-72 maOD) suggests that groundwater from within the mid-Cheshire ridge was much more likely to have discharged in a southerly direction towards it than in an easterly direction into the Delamere sandsheet. There are also at least two pieces of evidence which suggest strongly that the Fishpool was an active groundwater discharge feature before groundwater levels were lowered in the sandstone by pumping:

1) The valley feature containing the Sandyford Brook extends north-westwards from the present head of the brook to the Fishpool. It would appear that this upper part of the valley, which is now dry, was developed by groundwater discharge from the sandstone prior to the relatively recent lowering of groundwater levels through pumping.

2) The 1881-2 topographic survey (Figure 6.2) shows the Fishpool as a surface water feature forming the head of the Sandyford Brook.

The fact that recorded groundwater levels in the sandstone forming the mid-Cheshire ridge were very similar to groundwater levels in the Delamere sandsheet (both c. 73 maOD), and also that groundwater from a significant part of the mid-Cheshire ridge probably flowed in a southerly direction towards the Fishpool, suggests that relatively little groundwater flowed from the mid-Cheshire ridge into the Delamere sandsheet prior to 1905. Hence, when groundwater levels in the sandstone were lowered by pumping after 1905, the groundwater catchment area to Oakmere and Abbots Moss was probably relatively unchanged, meaning that both groundwater levels and the seasonal and medium-term variability of those levels also remained relatively unchanged. In turn, this indicates that long-term groundwater abstraction from the sandstone has most probably had a negligible effect on the groundwater regimes of Oakmere and Abbots Moss cSACs.

In order to extend the qualitative interpretation given above into a quantitative estimate of the degree to which the groundwater regimes at Oakmere and Abbots Moss have been altered by long-term pumping from the sandstone, exploratory groundwater modelling was carried out. Unfortunately, however, it was found at a relatively early stage that the combination of the complex hydrogeology of the area and the limited data availability on groundwater conditions prior to 1905 meant that the uncertainty associated with any modelling results would be too large for the results to be of any use in this context.

6.1.2 Groundwater abstraction from the Delamere sandsheet

The conceptual understanding of Oakmere, and by inference Abbots Moss, suggests that they are in good hydraulic continuity with the groundwater system. In simple terms, this means that surface water levels in Oakmere and Abbots Moss are simply an expression of the local water table.

In order to assess the possible effect of Agency-permitted groundwater abstractions on groundwater levels in the vicinity of the conservation sites, and therefore surface water levels within the sites, the following simple methodology was employed:

1) Calculate the average recharge rate for the period 1982-2002, based on the calculations described in Section 4.2.

2) For each abstraction, divide the licensed rate of abstraction (taking into account assumed consumptive use) by the average recharge rate to produce an area of influence, i.e. the area over which recharge accounts for the abstraction. Within this area, groundwater levels will be lowered by the abstraction.

3) Plot circles of appropriate area on a basemap to assess whether any of the abstractions are likely to lower groundwater levels in the vicinity of the conservation sites.

Figure 6.3 is the resulting map. It shows that the areas of influence of the majority of Agency-permitted abstractions are a significant distance from the conservation sites, and therefore that the abstractions will almost certainly not lower groundwater levels in the vicinity of either Oakmere or Abbots Moss.

It should be noted that a number of simplifying idealisations concerning the hydrogeological system are inherent in the technique used to assess the influence of abstraction on the conservation sites. The most significant of these are:

1) That groundwater flow takes place through a homogeneous porous medium.

2) That there is no natural hydraulic gradient across the sandsheet.

The first of these idealisations is considered to be reasonable as most of the geological logs from boreholes within the sandsheet included large thicknesses of homogeneous sands, although the influence of lower permeability clay horizons is uncertain. The second assumption is not valid, although over large areas in the centre of the sandsheet the hydraulic gradient is relatively low.

Whilst the simplifying idealisations inherent in the technique are not wholly valid, it should be noted that the effect of this on the areas of influence on Figure 6.3 is to modify their shape somewhat from an idealised circle, rather than changing their area. It can be seen in Figure 6.3 that only extreme (and unrealistic) distortion of the areas of influence would bring their boundaries close to either of the conservation sites. It is therefore concluded that the Agency-permitted abstractions have no influence on groundwater levels in the vicinity of either Oakmere or Abbots Moss.

In order to assess the possible effects during drought conditions, the exercise described above was repeated using the estimated recharge for the period 1995-6. The climatic conditions and resulting low groundwater recharge during this period caused the lowest natural groundwater levels since records began to be observed in most areas in the UK. Figure 6.4 is the resulting map. It shows that none of the areas of influence, when they are represented as circles, reach either Oakmere or Abbots Moss. It is, however, conceivable that the outer margin of the areas of influence of the larger abstractions to the north of Oakmere (Fourways and Crown Farm Quarries) could reach Oakmere through significant distortion of the circular areas of influence. It is concluded, therefore, that whilst being possible, it is unlikely that Agency-permitted groundwater abstractions from the Delamere sandsheet influenced groundwater levels in the vicinity of Oakmere or Abbots Moss during the extreme drought conditions of the period 1995-6.

6.2 Other possible influences

6.2.1 Introduction

During the course of the current project, a number of other possible influences on the hydrogeological environment, and therefore potentially on the conservation status of Oakmere and Abbots Moss, have been identified. In all cases, the nature of these possible influences means that the Agency does not have responsibility as an appropriate authority under the Habitats Regulations to carry out appropriate assessments. The possible influences are described briefly below.

6.2.2 Surface water lakes resulting from quarrying

The establishment of relatively large quarry lakes within the sandsheet has at least two significant hydrogeological effects:

1) Using the recharge model and figures for open-water evaporation, the water balance for the dominant land-use (grassland) over the sandsheet was compared with that for a body of open water. It was found that the average recharge for grassland was significantly more than the positive water balance for an open body of water, and therefore that quarry lakes represent a passive abstraction from the sandsheet. Over the total area of quarry lakes within the sandsheet, this passive abstraction equates to approximately 190 Ml/a. This is a significant figure (second highest) in comparison with the other groundwater abstractions (i.e., returns, taking into account consumptive use).

2) Removal of a large body of sand between the recharge and discharge areas for groundwater within the sandsheet will have led to a net increase in hydraulic conductivity. This increase in net hydraulic conductivity will have resulted in a lowering of groundwater levels across the sandsheet. It is not possible to assess the scale of this effect without further investigation.

6.2.3 Groundwater abstraction by Forest Enterprise

Groundwater is abstracted by Forest Enterprise under Crown exemption from two sites within the sandsheet (see Figure 3.9). Appropriate assessment of these abstractions would involve a simple application of the method used for the current project.

6.2.4 Changes in land-use, e.g., vegetation

Recharge dynamics, and therefore the groundwater balance local to the conservations sites, will be sensitive to variations in transpiration rate resulting from either life-cycle changes of a particular vegetation type (e.g., maturation of trees) or changes in vegetation type (Calder, 1990, Greene and Taylor, 1989). This sensitivity will be most important in close proximity to the conservation sites, e.g. in relation to the evergreen plantations and tree nursery close to Abbots Moss. It is not possible to assess the scale of this effect without further investigation.

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Figure 6.1 Extract from 1:25,000 O.S. map - Oakmere Fishpool area

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

Information on the geology and hydrogeology of the Delamere sandsheet and environs has been collated and interpreted to arrive at a detailed hydrogeological conceptual model of the area. A water balance calculation, based on this conceptual model, in which inputs (recharge) equalled outputs (groundwater discharge) within a reasonable error, offers confirmation of the validity of the conceptual model. The water balance shows that overwhelming majority of groundwater within the sandsheet discharges as baseflow to streams, with discharge into the Sherwood Sandstone aquifer to the west and abstraction representing much smaller proportions (c. 3% and 4% of total discharge respectively).

Stage III appropriate assessment under the Habitats Regulations is required for the Agency-permitted groundwater abstractions from both the Sherwood Sandstone and the Delamere Sandsheet.

In order to prove that a licensed abstraction has a significant impact, either individually or in combination with other consented activties, on a conservation site (i.e. cSAC), it is necessary to prove; a) that the licensed abstraction has a significant effect on groundwater levels and/or quality in the vicinity of the site, and b) that this significant effect has a significant impact on the conservation status, i.e., favourable or not favourable, of the site.

In the present case it has proved difficult to resolve the exact relationship between the conservation features of the cSACs (Oakmere and Abbots Moss) and the groundwater environment. It is, however, clear that Oakmere is in good hydraulic continuity with groundwater, and therefore that the level of Oakmere is generally the same as that of the local water table. Whilst surface water levels have not been available for the Abbots Moss site, it can be assumed that a similar situation to that at Oakmere pertains, i.e., that surface water at the site is in hydraulic continuity with groundwater. It should be noted that this is a worst-case assumption in relation to the assessment of the possible effects of Agency-permitted groundwater abstractions.

With regard to the Sherwood Sandstone, it is known that prolonged groundwater abstraction for public supply has caused groundwater levels to fall by approximately 30 m, causing an artificial hydraulic regime to be established. Interpretation of topographic and historical evidence suggests that this artificial hydraulic regime does not extend into the Delamere sandsheet, and therefore that the significant fall in groundwater levels in the sandstone has had little or no effect on the groundwater regimes of either Oakmere or Abbots Moss.

With regard to Agency-permitted groundwater abstraction from the Delamere sandsheet, simple hydrogeological modelling has been used to show that they have no influence on groundwater levels in the vicinity of Oakmere and Abbots Moss under 'average' climatic conditions (and groundwater recharge). Further modelling has shown that even under the drought conditions of the period 1995-6, which led to the lowest ever groundwater levels since records began, it is unlikely that the Agency-permitted groundwater abstractions from the sandsheet influenced groundwater levels in the vicinity of either Oakmere or Abbots Moss.

A number of factors other than Agency-permitted groundwater abstractions have been identified as having an effect on the hydrogeological environment of the sandsheet and therefore, possibly, an effect on the groundwater levels in the vicinity of Oakmere and Abbots Moss. These are; a) surface water lakes resulting from aggregate extraction, b) groundwater abstraction under Crown Exemption by Forest Enterprise, and c) changes in land-use (e.g., vegetation). The Agency is not the appropriate authority to carry out assessment under the Habitats Regulations of these possible influences.

7.2 Future monitoring requirements

Although it has been shown that the Agency-permitted groundwater abstractions in the area are unlikely to influence groundwater levels in the vicinity of Oakmere or Abbots Moss, even under drought conditions, there are some residual uncertainties in the hydrogeological conceptual model of the area. These are being addressed or will be addressed through the following investigation and monitoring activities:

- Monitoring of surface water and/or shallow groundwater levels in Abbots Moss, and especially in Shemmy Moss and South Moss.
- Water quality sampling in the piezometers surrounding Oakmere and Abbots Moss and surface waters within the sites themselves.
- Investigation of documentary or other evidence on the groundwater discharge-related processes operating in the Fishpool and Sandyford Brook prior to 1905.

Figure 6.2.dwg

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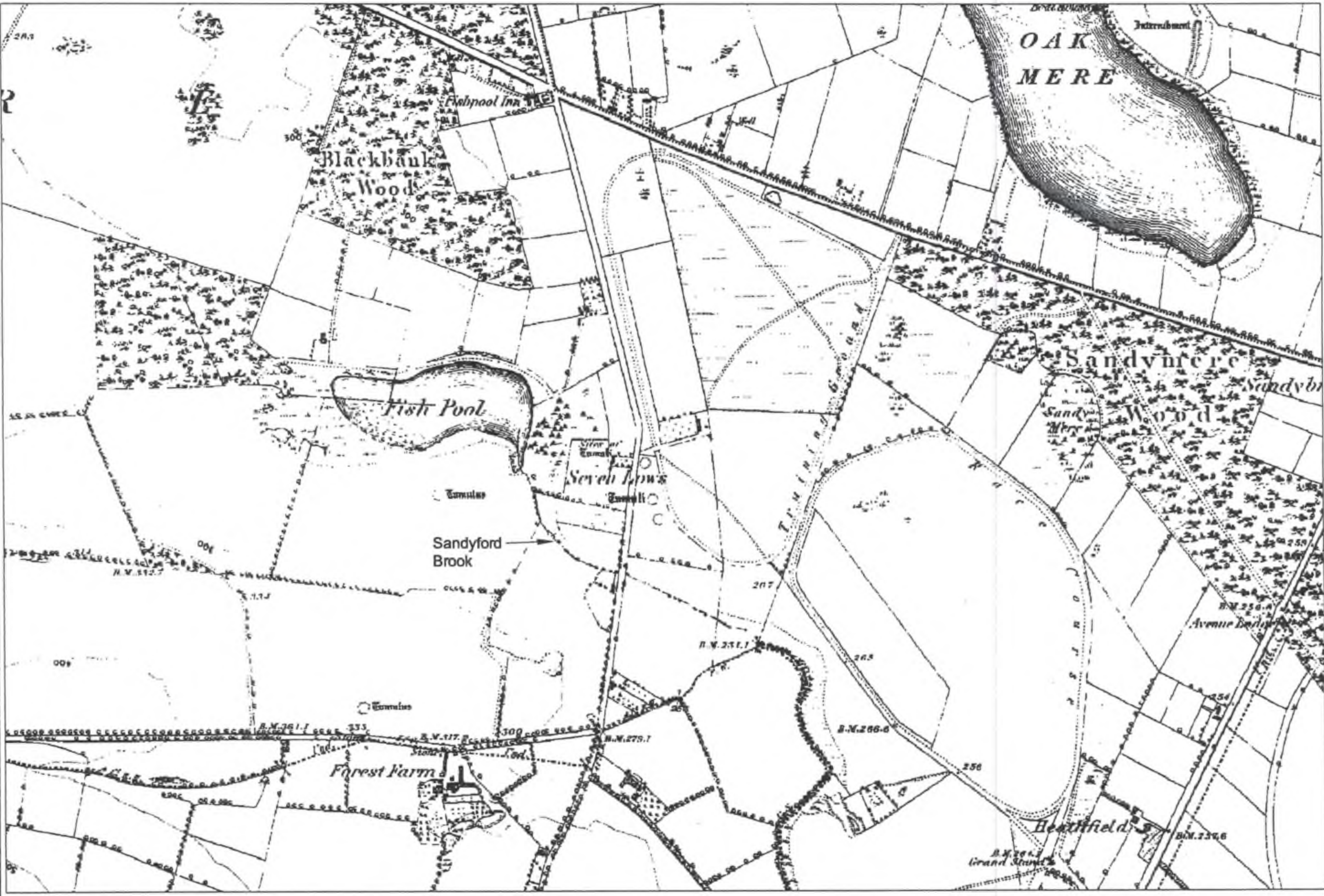

Figure 6.2 The Fishpool on 1881-2 topographic survey

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Figure 6.3 Areas of groundwater level influence for groundwater abstractions from sand sheet - average conditions (1982-2002)

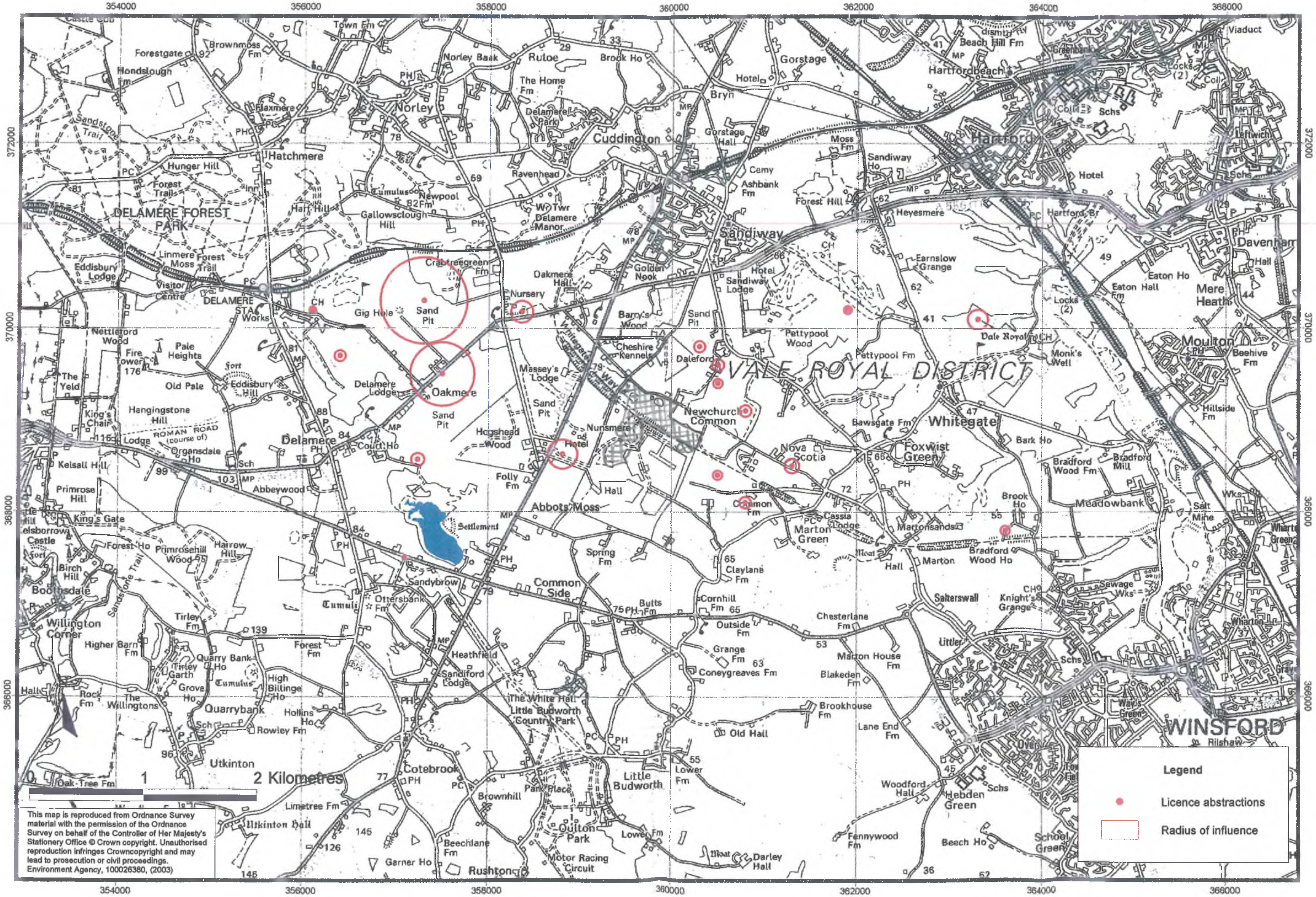

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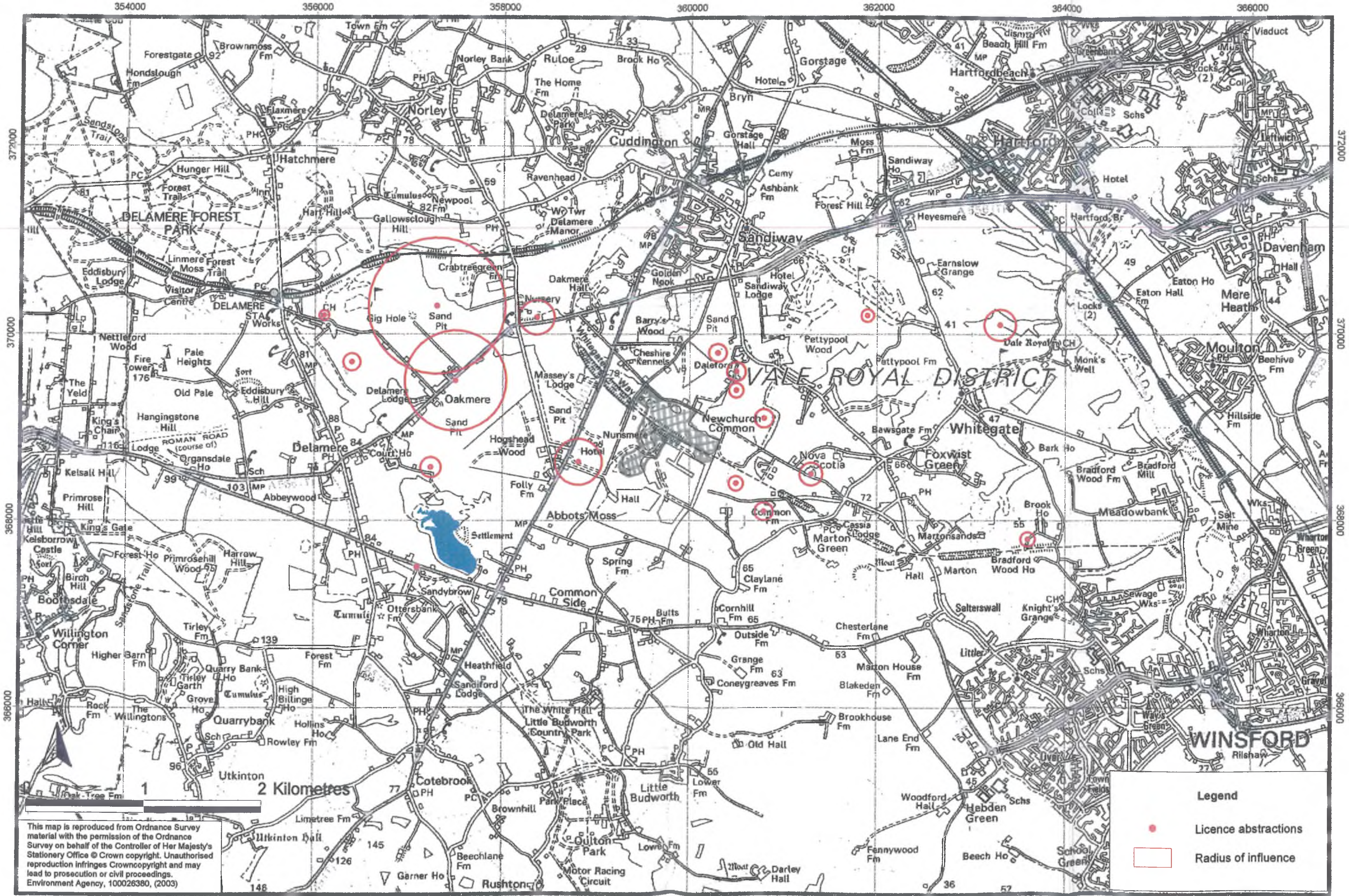
Figure 6.4 Areas of groundwater level influence for groundwater abstractions from sand sheet, drought conditions (1995-1996)



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